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Dynamics of litter decomposition and nutrient in different *Eucalyptus* stand in the Cerrado

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SIVICULTURE

ABSTRACT

Background: The aim of this study was to assess the decomposition of litter and subsequent nutrient release from different eucalypt stand with different clones in the neotropical savanna. Litter mass loss for each clone was assessed through the random distribution of over 1,080 litter bags on the soil surface. Chemical analyses of macronutrients (N, P, K, Ca, Mg, and S) and carbon (C) in the remaining litter were performed. An exponential and polynomial model was used to describe the decomposition and macronutrients, respectively. An ANOVA was conducted, and mean comparisons were performed using Tukey's test ($\alpha = 0.05$).

Results: At the end of the experiment, the remaining litter mass was 11% for clone GG100 and 15% for clone EAC 1528. The residual concentrations of C, K, and Mg in the litter were associated with mass loss, while N, P, Ca, and S increased up to 720 days. The levels of N, P, and Mg were higher in clone GG100, whereas Ca and S were higher in clone EAC 1528 ($p = 0.05$).

Conclusions: This study highlights that long-term research on litter decomposition in eucalypt stands contributes to a better understanding of nutrient cycling dynamics. Different eucalyptus stands exhibited distinct nutrient release patterns throughout the litter decomposition process.

Keywords: *Nutrient release; Clone GG100; Clone EAC 1528; Mass remaining.*

HIGHLIGHTS

GG100 showed higher concentrations of N, P, and Mg, whereas EAC 1528 had higher levels of Ca and S during litter decomposition.
Potassium (K) is rapidly released, while N, P, Ca, Mg, and S remain in the litter.
The dual exponential model provided a better fit for the decomposition of clone EAC 1528.
Litter releases nutrients slowly, contributing to long-term soil sustainability.

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INTRODUCTION

Litter plays a fundamental role in the functioning of forest ecosystems and is composed of all plant material deposited on the soil surface (Souza *et al*., 2025).The composition of this material is one of the main factors determining its residence time in the soil until complete decomposition (Wang *et al*., 2025a; Wang Lixia *et al*., 2025b). Understanding the functioning, interactions, and variables that influence litter decomposition is essential for the sustainable management of both native and planted forests (Valente *et al*., 2023).

Litter decomposition is a critical ecosystem process that links carbon (C) and nutrients above and below ground (Xu *et a*l., 2020). This ecologically important activity directly influences nutrient cycling and the functioning of various ecosystems (Souza *et al*., 2021). In dystrophic soils, typical of tropical regions, the recycling of nutrients through decomposition ensures the input of organic matter into the soil and the subsequent release of nutrients—albeit at a slower rate due to the unique characteristics of their respective cycles (Valadão *et al*., 2019). The decomposition rate of litter influences forest maintenance and is affected by natural factors, seasonality, floristic diversity, and temperature, all of which in turn impact the productivity and overall cycle of the ecosystem (Ribeiro *et al*., 2022; Viera *et al*., 2014a).

Planted forests provide a significant input of litter, thereby contributing to nutrient return and plantation sustainability (Magh *et al*., 2024). Commercial eucalypt plantations are economically important in tropical and subtropical regions (Lemessa *et al*., 2022; Santos *et al*., 2022), eucalypt is the most widely planted hardwood genus globally, covering approximately 25 million hectares (da Silva *et al*., 2020). In Brazil, planted forests occupy a substantial area of around 10.2 million hectares, with eucalypt being the predominant species, accounting for 76% of the total area of forest plantations in the country (IBÁ, 2024). This exotic species has adapted remarkably well to Brazilian conditions and plays a crucial role in the forestry sector's economy. In recent years, *Eucalyptus urophylla* x *Eucalyptus grandis* has become predominant in tropical regions of Brazil, primarily due to its rapid growth, superior basic wood density, resistance to water stress, and high yield (Silva *et al*., 2022). Among the various clones resulting from the hybridization of these two species, two are commercially prominent: GG 100 and AEC 1528.

Genetic material is another crucial factor to be considered in eucalypt plantations and must be selected based on location, environmental conditions, and edaphoclimatic characteristics (Inkotte *et al*., 2024; Siri *et al*., 2024). Given the rapid advancements in eucalypt breeding, particularly in terms of adaptation to water stress and resistance to pests and diseases, as well as the adoption of clonal propagation techniques, genotypes are quickly becoming obsolete and are being replaced by more productive ones after each harvest (Baesso *et al*., 2024). Considering Brazil's vast and diverse climatic zones, it is essential that selected clones are capable of withstanding water stress and, more importantly, nutrient limitations, while also ensuring phytosanitary stability at the planting site (Elli *et al*., 2020; Pimenta *et al*., 2024).

Currently, individuals with desirable traits for planting are selected using molecular markers associated with favorable ecophysiological behaviors, such as photosynthetic rates, root growth patterns, and carbon allocation (Oliveira, *et al*., 2020b; Pita-Barbosa *et al*., 2023; Teixeira *et al*., 2024). Enhancing the efficiency of natural resource use through genetic improvement and genotype-environment matching, alongside appropriate management practices, is a fundamental challenge to sustaining or increasing productivity (Sniezko *et al*., 2023).

Although numerous studies have been conducted to evaluate litter decomposition across a wide variety of perennial and forest species in Brazil—including eucalypt (Cunha *et al*., 2020; Ferreira *et al*., 2021; Moura *et al*., 2022)—long-term decomposition studies extending beyond one year are virtually non-existent. Despite scientific advances, significant knowledge gaps remain concerning the dynamics of eucalypt litter decomposition in naturally low-fertility soils, such as those found in the Cerrado, particularly regarding decomposition time. In this context, the present study aims to investigate the nutrient dynamics and litter decomposition of eucalypt with different stands in a Neotropical savanna (Cerrado) over a period of 1,890 days. This study aims to refine the soil residence time of this material and its nutrient dynamics.

MATERIAL AND METHODS

Study Site

The study was conducted in the rural area of Paranoá, Federal District, located within the neotropical savanna region (Cerrado) of Brazil. The study was conducted in two eucalypt stands (hybrids of *Eucalyptus urophylla* × *Eucalyptus grandis*), covering 12 and 19 hectares, respectively, and planted with clones EAC 1528 (coordinates: 15°53'S, 47°39'W; altitude: 948 m) and GG100 (coordinates: 15°53'S, 47°38'W; altitude: 946 m) (Figure 1).

Clone EAC 1528 was established in December 2011 at a spacing of 3.5 × 1.7 m. The area previously contained native Cerrado vegetation. For plantation establishment, the soil was tilled using a disc harrow to a depth of 15 cm and subsoiled along the planting lines to a depth of 90 cm. The mean diameter at breast height (DBH) of the trees was 13.4, 14.6, 15.5, 16.7, and 17.2 cm, and the mean height was 19.4, 22.6, 23.1, 23.7, and 24.1 m in the years 2014, 2015, 2016, 2017, 2018, and 2019, respectively. The average plant mortality rate observed over the study period was 4.5%.

Clone GG100 was established in December 2009, also at a spacing of 3.5 × 1.7 m. The area had previously been used for agriculture: soybean cultivation from 2003 to 2005, sorghum in 2006, and soybean again from 2007 to 2009. Soil preparation included strip tillage with a disc harrow to 15 cm depth and the use of a furrower in the center of the strip to a depth of 25 cm. The average DBH of the

trees was 15.4, 16.5, 17.2, 18.1, and 18.7 cm, and the average height was 24.4, 28.5, 30.0, 31.2, and 32.2 m in 2014, 2015, 2016, 2017, 2018, and 2019, respectively. The average plant mortality rate observed over the study period was 5%.

During the establishment of the eucalypt stands (E1 and E2), soil acidity was corrected by applying and incorporating dolomitic lime (2.5 t ha^{-1}) to a depth of 20 cm. Two months later, 700 kg ha^{-1} of agricultural gypsum was applied to the soil surface. Planting fertilization consisted of applying 200 g per plant of NPK (5-25-15). One year after plantation establishment (2010 and 2012), topdressing fertilization was carried out with 60 kg ha^{-1} of K_2O (as potassium chloride), 50 kg ha^{-1} of nitrogen (as urea), and 1 g of boron per plant (as borax). In January 2014, a new application of 60 kg ha^{-1} of K_2O was made.

The soil in the study areas is classified as dystrophic Red-Yellow Latosol, with a very clayey texture and a clay content ≥ 60%. The chemical attributes of the soil (0–10 cm depth) are presented in Table 1.

The regional climate is classified as tropical savanna (Aw) according to Köppen's system, with two well-defined seasons: a dry season from May to September and a rainy season from October to April. During the study period, the average air temperature ranged from 21.29 to 22.22 °C, and annual rainfall varied from 991.1 to 1519.0 mm (Figure 2), based on data from the Climatological Station of the Technical Assistance and Rural Extension Company of the Federal District (Emater-DF).

Litter Analysis

For the evaluation of the remaining litter mass per area, 1080 litter bags (20 x 30 cm, made of 2 mm nylon mesh) were randomly distributed on the forest floor. The litterfall was collected manually from the ground. The organic material has recently in the ground were collected, considering the edge effect. The initial weight of each litter bag was 20 g of dry material (Santos; Whitford, 1981). From August 2014 to November 2019, every three months 54 litter bags were collected and analyzed.

The litter was packed in labeled paper bags, sealed and sent to the laboratory to determine the fresh weight. Thereafter, the material was dried to constant weight in a forced air circulation oven (at 65 °C for 72 h) and then weighed again to determine dry weight.

Of the remaining mass and litter layer 1.0 g litter samples were ground in a mortar and sieved (0.2 mm), and subsequently the total C content was determined using a Vario MACRO cube Elementary analyzer (Elementar Analysensysteme, Hanau, Germany).

For nutrient chemical analysis, the litterfall samples were dried in a forced-air oven at 65 °C for at least 72 hours

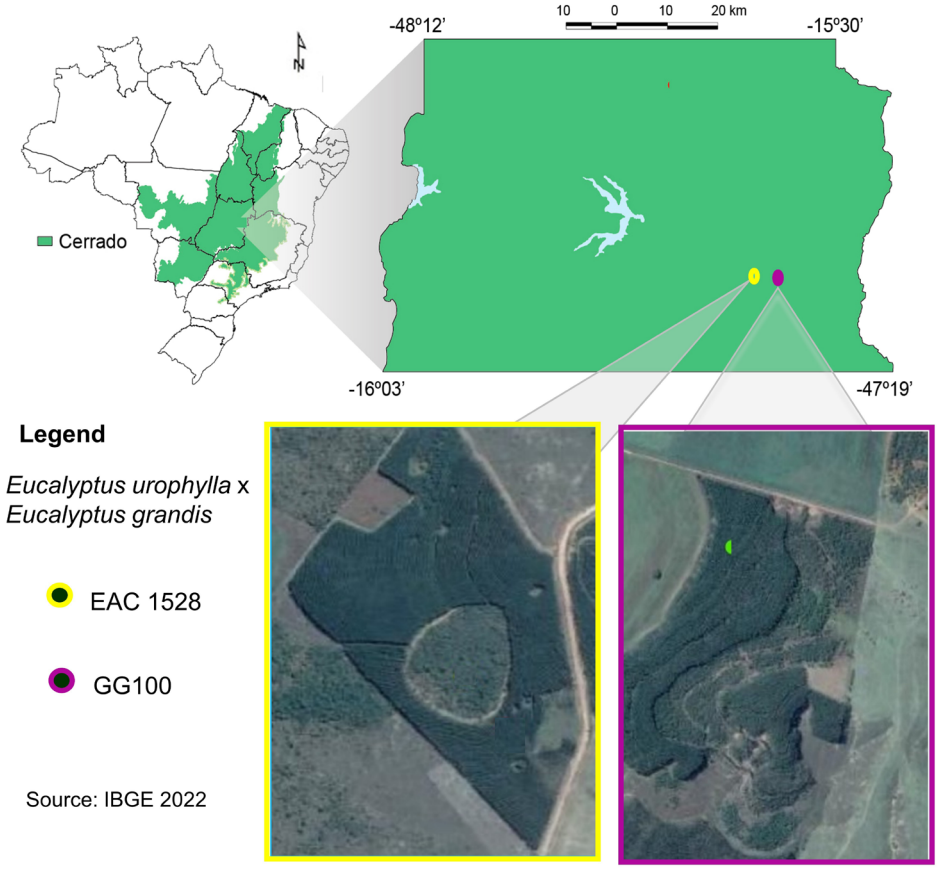

Figure 1: Location map two hybrids stands of *Eucalyptus urophylla* × *Eucalyptus grandis* with different ages: EAC 1528 (34-94 months) and GG100 (58-112 months) Distrito Federal, Brazil.

Table 1: Soil chemical properties in the layers (0-10 cm) in the three studied areas, two hybrids stands of *Eucalyptus urophylla* × *Eucalyptus grandis* with different ages: EAC 1528 (34-94 months) and GG100 (58-112 months) Distrito Federal, Brazil.

Property [(1)]		EAC 1528	GG100
		---------- 0-10 cm ----------	
OM	(dag kg^{-1})	3.1	2.8
pH	(H_2O)	4.95	5.35
P*	(mg dm^{-3})	1.45	4.4
H+Al	($cmol_c$ dm^{-3})	8.25	7.05
Sum of base	($cmol_c$ dm^{-3})	1.7	3.45
CTC	(cmolc dm^{-3})	9.9	10.5
V	%	16.75	32.35
B	mg dm^{-3}	0.5	1
Zn	mg dm^{-3}	0.3	0.95

OM: organic matter, Walkey-Black method; pH in water, 1:2.5 soil:solution relation; H+Al: potential acidity, extractor calcium acetate 0.5 mol L-1 pH 7; CEC: cation exchange capacity; B: hot water extractor; Zn: extractor Mehlich-1.

until constant mass was achieved. The dried samples were then weighed and ground to determine macronutrient contents. Nitrogen was determined via sulfuric acid digestion followed by the Kjeldahl method, while sulfur was analyzed via turbidimetry. The samples were subjected to nitric-perchloric digestion for determination of Ca, Mg, P, K, S, Fe, Zn, Cu, and Mn concentrations. Phosphorus and sulfur were measured using a molecular absorption spectrophotometer; potassium by flame emission photometry; and calcium, magnesium, iron, zinc, copper, and manganese by atomic absorption spectrophotometry. Boron content was determined after muffle furnace combustion at 600 °C, using a spectrophotometer and the azomethine-H method (Wolf, 1974). Due to the limited remaining material, litterfall was analyzed only up to 1080 days.

Data Processing and Analysis

A total of 6 random plots measuring 20 × 30 m were set up within from August 2014 to November 2019, every three months 9 per plot litter bags were collected and analyzed, totaling 720 litter bags.

Litter decomposition per area was calculated as proposed by (Santos; Whitford, 1981), based on the decomposition percentage, where the remaining litter rate was determined as the difference between the initial total litter mass amount (100 %) and each rate per assessment period. To calculate the decomposition rate constant (k), the double exponential model with two parameters was used (Equation 1), as applied by (Plante; Parton, 2007):

$$y = A\, e^{-kAt} + B\, e^{-kBt} \quad (1)$$

Where y is the amount of dry matter remaining (kg ha^{-1}) after a given time t (in days); A and B are constants; kA is the decomposition rate constant for the labile (rapidly decomposing) fraction; and kB is the recalcitrant decomposition constant. Both constants were estimated using Sigma Plot for Windows version 15.0, based on litterfall data obtained from litterbags over a 1,890-day period.

Another useful indicator for assessing the decomposition of plant material is the half-life ($t_1/_2$), which represents the time required for half of the litter mass to decompose or for half of the nutrients contained in that litter to be released. According to (Olson, 1963), the half-life can be calculated using the following equation:

$$t_{1/2} = \ln(2) / k = 0{,}693/k \quad (2)$$

Where $t_1/_2$ is the half-life of the remaining material; ln(2) is a constant; and k is the decomposition rate constant. The mathematical equations that best represented the dry matter decomposition were obtained using the Sigma Plot software.

The decomposition constant (k) allows to calculate the time projection required for the disappearance of 95 % (t = 3 / k)(Olson, 1963).

The function used for the nutrient contents (N, Ca, K, P, Mg and S) for the different stand studied (EAC 1528 and GG100) a cubic polynomial model was employed.

Statistical analysis of the treatments was performed using analysis of variance (ANOVA). Subsequently, mean comparisons of nutrient and carbon contents were conducted using Tukey's test at a 5% significance level. All analyses were carried out using Sisvar software, version 5.5.

RESULTS

The exponential regression curves demonstrate the biomass loss over a total period of 1,890 days (just over five years) for clones EAC 1528 and GG100. The models showed high accuracy, with R^2 values ≥ 0.98 and significance at the 1% level. Litter decomposition during the evaluation period was faster for clone GG100 on most sampling days ($p > 0.05$) (Figure 3a). The remaining litter mass for clone EAC 1528 was 58% at 360 days, 39% at 720 days, 30% at 1,080 days, 21% at 1,440 days, and 15% at 1,800 days, while for clone GG100 it was 51% at 360 days, 37% at 720 days, 28% at 1,080 days, and 11% at 1,800 days. At the end of the

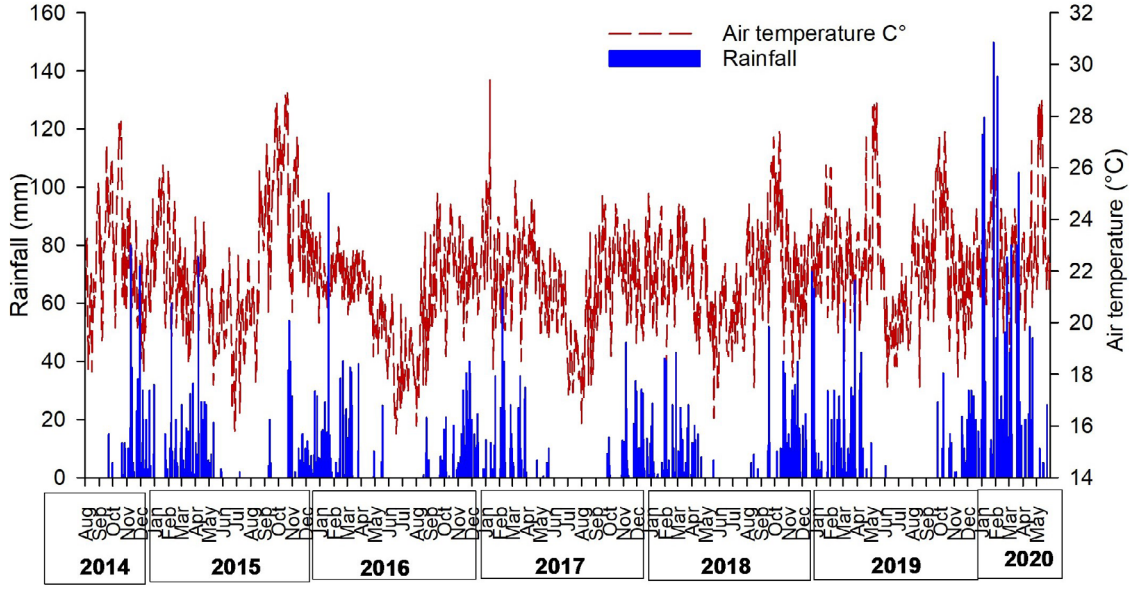

Figure 2: Rainfall (mm) and air temperature (°C) from August 2014 to November 2019 in Paranoá, Federal District, Brazil. Source: Emater-DF.

sampling period (1,890 days), the remaining biomass was 14% for EAC 1528 and 10% for GG100 (Figure 3b).

The half-life and the estimated time for 95% litter decomposition were 450 and 2,000 days for clone EAC 1528, and 360 and 1,710 days for clone GG100, respectively. The model accurately estimated the time to decompose 50% of the EAC 1528 litter, with only a 12-day difference between observed and predicted values, and also provided a reasonable estimation for the time required to decompose 95% of the material. For GG100, however, the model overestimated the time for 50% decomposition and underestimated the time for 95% (Table 2).

The carbon concentrations (C) in the litter for both clones are presented in Figure 4a. The C content ranged from 42 to 57 dag kg^{-1} for EAC 1528 and from 39 to 60 dag kg^{-1} for GG100. No significant differences in C concentrations were observed between the clones. When comparing sampling days, the C concentration for EAC 1528 showed no significant differences, whereas GG100 exhibited higher C values at 90 days compared to 990 and 1,080 days ($p > 0.05$). The regression models did not adequately fit the C concentration data, despite showing a general decreasing trend over time. The C:N ratio at the beginning of the evaluation ranged from 77:1 to 85:1, decreasing until 450 days and increasing again after 720 days (Figure 4b). No significant differences in mean C:N ratios were observed between the clones. For EAC 1528, the C:N ratio at time 0 was higher than at 540 and 630 days ($p > 0.05$). Similarly, GG100 showed a higher C:N ratio at time 0 compared to 630 days ($p > 0.05$).

The best-fitting model to describe variations in macronutrient concentrations (N, P, K, Ca, Mg, and S) was a cubic polynomial model: $f(x) = y_0 + a{\cdot}x + b{\cdot}x^2 + c{\cdot}x^3$, with R^2 values < 1.0 for both clones (Figure 5). The nitrogen (N) concentration in litter increased by 145% for EAC 1528 and 156% for GG100 between day 0 and day 630, followed by a decline until the final sampling day (1,080 days) (Figure 5a).

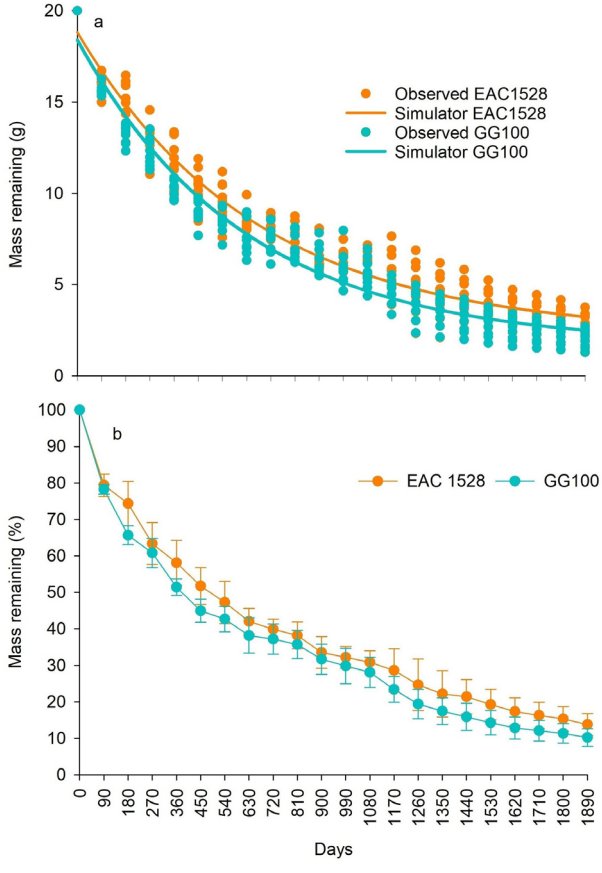

Figure 3: Curves exponentials (a) and percentage of the remaining (b) litter mass during decomposition over 1890 days, two hybrids stands of *Eucalyptus urophylla* × *Eucalyptus grandis* with different ages: EAC 1528 (34-94 months) and GG100 (58-112 months) Distrito Federal, Brazil.

No significant differences in N concentrations were observed between clones. Within the sampling periods, EAC 1528 had higher N concentrations only at 630 days compared to time 0 ($p > 0.05$). GG100 showed significantly higher N at 630 days compared to 0, 90, and 1,080 days ($p > 0.05$).

Phosphorus (P) concentrations increased by 50% from the beginning to 630 days for EAC 1528, and by 83% up to 900 days for GG100, after which both clones showed declining P levels (Figure 5b). P concentrations were significantly higher in GG100 compared to EAC 1528 from 90 to 990 days ($p > 0.05$). Additionally, GG100 had higher P concentrations at 810 and 900 days compared to 0 and 1,080 days ($p > 0.05$).

Potassium (K) concentrations in the litter decreased by approximately 90% from the beginning to the end of the study for both clones (Figure 5c). No significant differences were observed between the clones. Over time, EAC 1528 showed higher K concentrations at time 0 compared to the period from 540 to 1,080 days ($p > 0.05$). GG100 exhibited higher K concentrations up to 360 days compared to the later periods ($p > 0.05$).

Calcium (Ca) concentrations increased by 94% for EAC 1528 up to 810 days, while GG100 showed a 42% increase up to 720 days. After these points, Ca concentrations declined for both clones (Figure 5d). Ca concentrations were significantly higher for EAC 1528 from 270 days onward ($p > 0.05$). When comparing sampling periods, EAC 1528 showed significantly higher Ca at 810 days compared to 0, 90, and 180 days ($p > 0.05$). Clone GG100 showed no significant differences among the evaluated time points ($p > 0.05$).

Magnesium (Mg) concentrations decreased by 54% and 31% from the start to the end of the study for EAC 1528 and GG100, respectively (Figure 5e). EAC 1528 had higher Mg at time 0 compared to 1,080 days ($p > 0.05$). For GG100, Mg was significantly higher at 180 days than at 1,080 days ($p > 0.05$). GG100 also showed higher Mg concentrations than EAC 1528 at 90, 180, 270, 360, 450, 990, and 1,080 days ($p > 0.05$).

Sulfur (S) concentrations increased by 97% for EAC 1528 up to 900 days, and by 45% for GG100 up to 810 days, followed by reductions for both clones (Figure 5f). S concentrations were higher for EAC 1528 at 270, 540, 720, 810, 900, 990, and 1,080 days ($p > 0.05$). When comparing across time, EAC 1528 had higher S levels at 540, 720, 810, 900, and 990 days than at 0, 90, and 180 days ($p > 0.05$). For GG100, no significant differences were observed between time points ($p > 0.05$).

DISCUSSION

Litter Decomposition

Overall, clone GG100 exhibited greater litter decomposition. In forest stands, litter decomposition rates may vary depending on species characteristics (Kooch; Samadzadeh; Hosseini, 2017). Silvicultural practices such as planting density, stand spacing (Chen *et al*., 2019a) and climatic conditions (temperature, humidity, and precipitation) (Feng *et al*., 2025) were similar between the two study areas, with differences observed primarily in tree age (Corrêa *et al*., 2016), clone type (Conti Júnior *et al*, 2017), and soil chemical quality (Oliveira, *et al*., 2020a).

In eucalypt stand, canopy height and closure jointly regulate litter decomposition by moderating the understory microclimate. As stands mature and grow taller, they create a stable, humid environment—characterized by reduced wind and temperature fluctuations—that promotes biotic decomposition. Recent research confirms that these closed, taller canopies support faster decomposition compared to younger stands, which suffer from radiation-induced (Skorupa *et al*., 2015; Inkotte *et al*., 2023). Ultimately, the increased litter input and microclimatic buffering in taller stands underscore the canopy's role in driving nutrient cycling and soil carbon return (Balbinot *et al*., 2024).

Clone GG100 presented a half-life of 360 days, while clone EAC 1528 required approximately three additional months to decompose 50% of its litter. One reason the model accurately estimated the decomposition period for EAC 1528 is that the Eucalypt genus typically has low litter decomposition rates, often below 50% within 360 days, and maintains a high C:N ratio throughout most of the evaluation period—regardless of management practices or edaphoclimatic conditions (González *et al*., 2023; Ribeiro *et al*., 2018). The chemical composition of eucalypt leaves may hinder microbial colonization due to the presence of essential oils and other allelopathic compounds, which inhibit microbial establishment and activity, delaying decomposition and mineralization (Ferreira *et al*., 2016).

In a study on litter dynamics of GG100 and EAC 1528 clones, (Ribeiro *et al*., 2018) observed that GG100 produced more litter, which increased soil moisture, thereby enhancing decomposer efficiency and improving both the chemical and physical environment, thus accelerating decomposition (Olsson *et al*., 2019).

Faster decomposition at the beginning of the evaluation was due to fragmentation by physical agents, soil biota, and the release of more soluble compounds such as sugars, starches, and proteins, which are rapidly utilized by decomposers (Scheer, 2008; Swift *et al*., 1979). Over time, more resistant components—recalcitrant fractions rich in lignin, cellulose, hemicellulose, and structural tissues such as veins and petioles—remained, reducing the rate of decomposition (Lima *et al*., 2015; Viera *et al*., 2014b).

Macronutrient Dynamics During Decomposition

The remaining C, K, and Mg in the litter were closely related to the overall litter mass loss, due to their positive correlations with remaining biomass. Carbon dynamics in the litter were consistent throughout the evaluation period for both clones. During the early stages of decomposition, organic matter retains high C content (Baietto *et al*., 2021a), which limits the immediate release of nitrogen. In addition to the C:N ratio, the composition of the microbial community is a critical factor influencing nitrogen mineralization potential (Santos *et al*., 2018). However, as soil microorganisms consume the more easily degradable materials, the decomposition rate slows, while the relative proportion of nitrogen—mainly in the form of

Table 2: Litter decomposition parameters obtained through exponential regression to two hybrids stands of *Eucalyptus urophylla* × Eucalyptus grandis with different ages: EAC 1528 (34-94 months) and GG100 (58-112 months) Distrito Federal, Brazil.

Equation	EAC1520	GG100
	$y=2.2860 +16.5418\ e^{-0.0015}$	$y=1.6992 + 16.7035\ e^{-0.0016}$
k	0.0015	0.0016
Time 1/2 observed	450	360
Time 1/2 Simulated	462	433
Time 0.95 Simulated	2000	1875

ammonium (NH_4^+)—tends to increase (Santos *et al.*, 2018). This occurs because carbon is rapidly lost as carbon dioxide (CO_2), while nitrogen is retained, accumulating in microbial biomass and more recalcitrant litter fractions (Ahmed *et al.*, 2022). As a result, a progressive increase in residual nitrogen concentration in the litter is observed.

In general, the dynamics of N, P, Ca, and S in the litter showed alternating patterns of immobilization and mineralization for both clones. These patterns are likely driven by microbial nutrient demand (Chen *et al.*, 2019b).

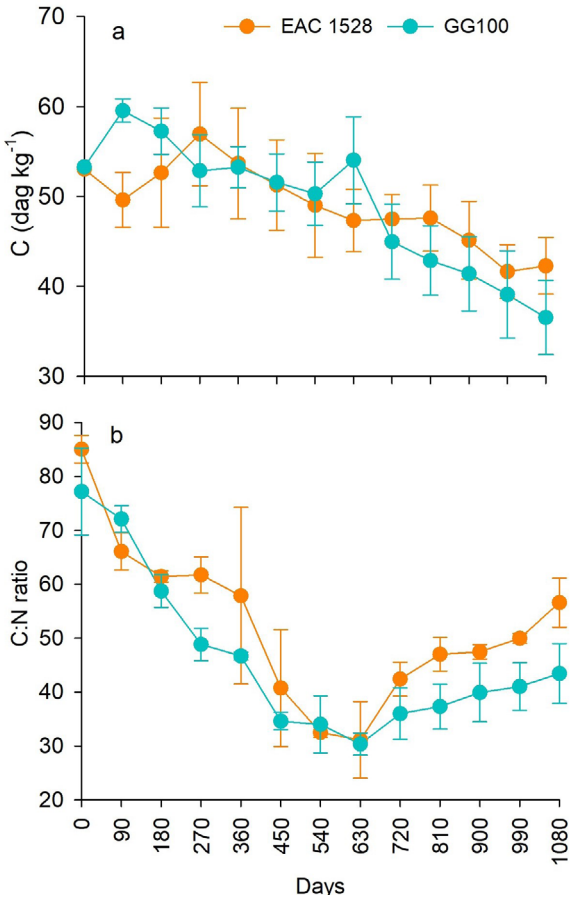

Figure 4: Concentrations of carbon (C) (a) and Pattern of the C:N (b) two hybrids stands of *Eucalyptus urophylla* × *Eucalyptus grandis* with different ages: EAC 1528 (34-94 months) and GG100 (58-112 months) Distrito Federal, Brazil.

Nitrogen immobilization in Eucalypt plantations has been reported during the initial stages of decomposition in other studies (Schlesinger; Bernhardt, 2020). Thus, soil fertility may influence nutrient immobilization or mineralization patterns (Bonanomi *et al.*, 2017).

Among the macronutrients, phosphorus (P) was observed at lower concentrations in both clones. Tropical soils naturally have low levels of mineral P, and even when fertilization occurs, the recovery rate by plants tends to be low due to complex physicochemical processes such as adsorption, fixation, and precipitation, making P relatively immobile (Fink *et al.*, 2014). It is worth noting that P is one of the most mobile elements within plants due to high internal translocation (Srivastava *et al.*, 2018). Moreover, P is a critical nutrient for plant development and can influence litter decomposition by altering microbial biomass and community structure (Kurita *et al.*, 2022; Zhang *et al.*, 2020). In this study, higher residual P was observed in the litter of clone GG100, which may be partly explained by prior agricultural use of the area, as shown in Table 1—where the GG100 site contained nearly three times more P in the soil compared to the EAC 1528 site.

Potassium (K) was the most rapidly released nutrient, regardless of clone. It was the only nutrient to exhibit a similar quantitative pattern of release during the entire decomposition process (Figure 5). K is the most abundant cation in plants and is essential for various physiological processes (Jeschke *et al.*, 1987). K exhibited the highest percentage of release during decomposition, with a 68% reduction in EAC 1528 and 53% in GG100 within the first 90 days. Some studies report that up to 60% of K may be leached within the first month, and over 80% within three months (Momolli *et al.*, 2018). suggesting leaching is a key mechanism in K transfer to the soil.

The relatively high Ca concentration in litter, regardless of clone, may be due to its low mobility within plant tissues. It is mainly found in lignified tissues because of its structural role in pectic chains within the cell wall (Hawkesford *et al.*, 2012). Due to its limited internal translocation, Ca cycling in the environment is largely dependent on leaf litterfall and decomposition (Mayta *et al.*, 2019). The higher Ca content in clone EAC 1528 compared to GG100 may be explained by stand age, as Ca concentrations in eucalypt leaves tend to decrease over time.

Magnesium (Mg) dynamics are closely linked to biomass loss in Eucalypt species (Baietto *et al.*, 2021b),

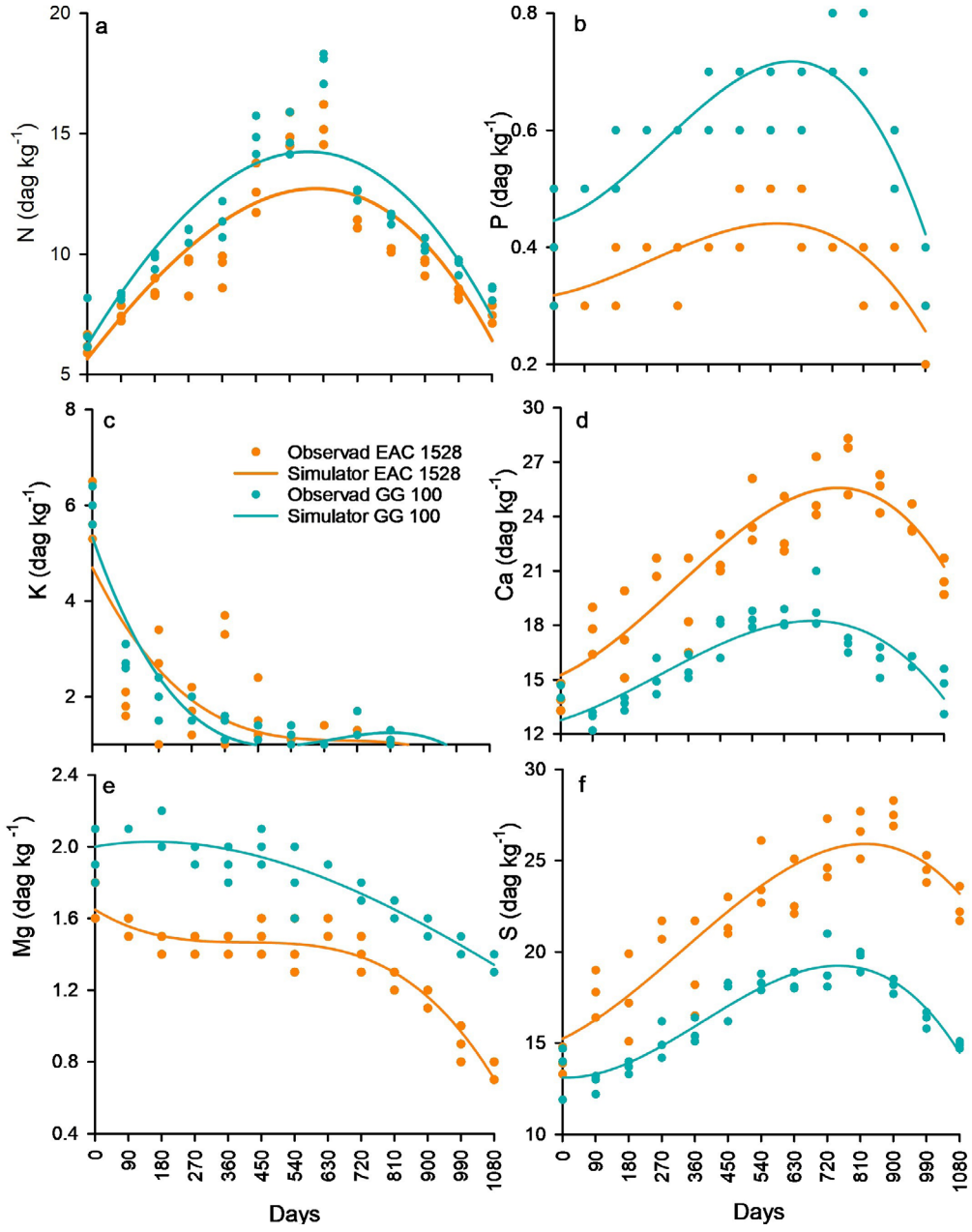

Figure 5: Macronutrient content in litter mass during decomposition over a 1080-day period was described using a cubic polynomial model, two hybrids stand of *Eucalyptus urophylla* × *Eucalyptus grandis* with different ages: EAC 1528 (34-94 months) and GG100 (58-112 months) Distrito Federal, Brazil.

particularly in the foliar fraction (Moura *et al*., 2022), which was evident in both clones. However, despite its faster decomposition, clone GG100 released less Mg into the system. The amount of accumulated litter on the soil surface is associated with reduced Mg concentrations in eucalypt leaves, and higher annual Mg losses have been reported in eucalyptstands on Cerrado Oxisols with limited organic cover (Valadão *et al*., 2021).

Sulfur (S) is a secondary macronutrient that, like N and P, is found in high concentrations in eucalypt leaves (Alvarez *et al*., 2008), with increasing concentrations observed in both clones up to 810 days. S is predominantly present in plant tissue as amino acids, thus strongly correlating with nitrogen (Turner *et al*., 2016). Despite its rapid release into the soil, S is typically among the last macronutrients to be transferred from litter to soil annually (Ludvichak *et al*., 2016).

The total nutrient content in litter reflects the concentration of elements in plant tissues and the quality of the litter produced (Bündchen *et al*., 2013). Taken together, the results indicate that nutrient decomposition is strongly modulated by the structural and functional characteristics of different stands, including age, canopy height, and degree of canopy closure. These differences promote the

development of distinct microclimates, which influence soil water and thermal availability, rainfall interception, and understory ventilation, in addition to shaping the edaphic environment and the composition of the decomposer community. Consequently, variations are observed in nutrient release rates and in the residence time of litter in the soil among stands, reflecting the interaction between climate, canopy structure, and litter quality. These findings highlight the importance of considering stand structural attributes and environmental variability when assessing nutrient cycling.

CONCLUSIONS

The dual exponential model provided better estimates of decomposition and half-life for clone EAC 1528.

Nitrogen, phosphorus, and magnesium concentrations were higher in clone GG100, whereas calcium and sulfur concentrations were higher in clone EAC 1528 throughout the decomposition period.

Foliar litter serves as a long-term reservoir for N, P, Ca, Mg, and S, while potassium (K) is rapidly mineralized, with nearly complete release during early decomposition stages.

Litter serves as a source of essential nutrients for long-term plant development, releasing nutrients slowly yet gradually, thereby minimizing losses within the soil–plant–soil system.

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AUTHORSHIP CONTRIBUTION

Project Idea: FPR
Database: FPR, ADO, AG
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Data availability:

The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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