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Soil Management and Topsoil Quality as Determinants of Residue Decomposition and Nutrient Release in Agroecosystems of the Brazilian Cerrado

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Abstract

Nutrients and carbon cycling processes in integrated production systems are essential for agroecological sustainability in the Cerrado of Northeast Brazil. However, quantitative and process-level understanding remains limited. This study aimed to characterize off-season plant residue decomposition under different production arrangements through the assessment of dry biomass, bromatological composition, and litter decomposition kinetics. The experiment was conducted in the off-season of the 2022/2023 agricultural year at Barbosa farm (Brejo, Maranhão, Brazil), in a Yellow Argisol (Ultisol), with Aw prevailing climate. We evaluated residues of soybean, *Urochloa brizantha* cv. Marandu, maize, maize + Marandu, *Megathyrsus maximus* cv. BRS Tamani, *Eucalyptus*, Eucalyptus + Tamani, and native forest, representing crop–livestock integration (CLI), livestock–forestry integration (LFI), no-tillage soybean (Soybean-NT), and native forest (control). For each treatment, 0.20 × 0.20 m, 2 mm mesh nylon litterbags (n° = 4 replicates) were filled with 20 g of oven-dried plant residues cut into ~10 cm pieces. Litterbags were placed on the soil surface and sampled at 0, 30, 60, and 118 days to estimate the decomposition rate (k), C and N mineralization, and macronutrient dynamics. Residues differed in initial composition, with *Eucalyptus* and Eucalyptus + Tamani showing higher C contents (41–43%), while Marandu and Soybean-NT had greater concentrations of N (37.8–39.2 g kg^{-1}), P (2.37–2.42 g kg^{-1}), and Mg (2.38–2.83 g kg^{-1}). The Eucalyptus + Tamani mixture exhibited the highest decomposition rate (k = 0.0041), which was about 40% greater than Soybean-NT (k = 0.0026), and faster C release, whereas N in maize residues remained immobilized for up to 118 days. CLI and Soybean-NT enhanced nutrient cycling efficiency, with K+ increasing 17.3-fold (1.1 to 18.9 g kg^{-1}) and N 1.2-fold (1.8 to 2.3%) compared to native forest. Overall, residue quality, especially C/N ratio and lignin, regulated decomposition and integrated systems, particularly LFI, which conferred greater resilience and nutrient cycling efficiency in the Cerrado.

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1. Introduction

The pursuit of sustainable management practices in expanding agricultural regions is urgent, particularly in the Cerrado biome, which plays a pivotal role in Brazilian agriculture. Within this context, the MATOPIBA region (Maranhão, Tocantins, Piauí, and Bahia states), especially the northern states of Piauí and Maranhão, stands out for its intense agricultural activity. However, in this agricultural area, significant knowledge gaps remain regarding the dynamics of plant residue decomposition and its interactions with different management systems.

Integrated production systems have been shown to play a pivotal role in enhancing agricultural sustainability in the Cerrado. By influencing soil microbial and faunal communities, these systems contribute to more efficient nutrient cycling [1–3]. Funnicelli et al. [4] found that different cropping systems modulate soil microbial structure and identified key bacterial communities involved in nutrient cycling in crop–livestock–forestry systems in MATOPIBA. Similarly, Santos et al. [5] established clear links between soil fauna diversity and soil health in integrated systems, especially regarding the soil's organic carbon content. These findings build upon earlier work by Leite et al. [6] on plant residue decomposition in Oxisols of the Cerrado in Maranhão state. Additional studies demonstrate increased biological activity [7,8] and organic C stocks in soils [9], further underscoring the strategic role of these systems in sustainable agricultural development.

The integration of annual crops, pastures, forestry components, and livestock [3,10] offers benefits extending beyond environmental gains. In Piauí and Maranhão states, Brito et al. [11] and Silva et al. [8] reported significant increases in soybean yields when rotated with maize intercropped with forages. Collectively, these results and the continued expansion of such practices in Northeastern Cerrado highlight the need for further research into the biogeochemical mechanisms affecting plant residue decomposition and nutrient cycling. This knowledge is essential to optimize management protocols and maximize benefits across diverse agricultural contexts in the region.

Preliminary results indicate that the decomposition of forage grass residues in integrated systems can synchronize nutrient release with the increased nutrient demand of soybean plants, thereby enhancing yields [11]. Nonetheless, the inherent complexity of integrated systems arising from the wide range of possible spatial and temporal arrangements requires careful assessment of how different soil management practices and plant residue configurations influence production, residue decomposition, and nutrient release. A critical factor in this context is the rate of carbon (C) and nitrogen (N) mineralization, which is directly linked to plant residue decomposition dynamics [12]. Efficient mineralization can substantially improve soil fertility and agricultural productivity [13]. The effects of plant residue decomposition on subsequent crop productivity depend on both the chemical composition of the residues and the characteristics of the soil [14,15].

Despite advances, understanding the factors influencing decomposition, such as residue quality, management systems, environmental conditions, and soil properties, remains limited. Evidence shows that soil moisture and temperature are key drivers of this process, directly affecting microbial activity and mineralization rates [1,16–19]. Integrative analyses of these factors have demonstrated the potential to enhance nutrient cycling in sustainable agricultural systems [20–22].

Given this background, it is essential to investigate how different components of integrated cropping systems combining grain production with pastures and trees affect residue decomposition rates and the release of C and N from litter. Accordingly, this study tested the following hypotheses: (i) integrated systems with the presence of an animal component accelerate residue decomposition compared to systems without animals (soybean cultivation and native Cerrado), regardless of residue quality, and (ii) the decomposition rate of mixed residues from different species is greater than that of residues from an individual species. To test these hypotheses, a field experiment was conducted in order to evaluate dry matter production, chemical composition, decomposition rates, and nutrient cycling in integrated production systems in the off-season.

2. Materials and Methods

2.1. Characterization and History of Study Sites

A litterbag study was carried out at Barbosa farm, in the municipality of Brejo, Maranhão state, Brazil (03°42′44″ S; 42°55′44″ W), at an altitude of 104 m above sea level. The native vegetation is classified as Cerrado *stricto sensu* [23]. The terrain is flat to gently undulating, and the soil is classified as Yellow Argisol [24], corresponding to Ultisol [25]. The regional climate is hot, humid tropical (Aw, Köppen classification), with a mean annual precipitation of 1825 mm and a mean annual temperature of 27 °C [26]. The geographical location of the study area is shown in Figure 1, and the rainfall distribution during the experimental period is presented in Figure 2.

In May 2022, soil samples were collected from the 0.00–0.10 m layer to assess chemical properties, following the methodologies described by Raij et al. [27] and Teixeira et al. [28]. This layer was selected because, under tropical conditions, soil processes such as litter decomposition and nutrient cycling are most active in the surface soil, and deeper layers are less affected by these processes [29,30]. The analyzed chemical parameters are presented in Table 1, and the land use history and specific characteristics of each system evaluated are presented in Table S1.

Table 1. Detailed soil characteristics for each agricultural production system and native Cerrado vegetation at the 0.0–0.10 m layer (n = 4 replicates). Brejo, Maranhão state, Brazil.

Soil Attributes	CLI	LFI	Soybean-NT	Native Vegetation
pH ($CaCl^2$)	4.67	5.07	5.10	4.23
TN (g kg^{-1})	1.56	3.10	2.06	1.31
S (mg dm^{-3})	2.99	5.68	3.42	5.20
P (mg dm^{-3})	36.78	6.87	26.34	3.10
K+ (cmolc dm^{-3})	0.17	0.19	0.06	0.02
Ca (cmolc dm^{-3})	0.85	2.24	1.75	0.28
Mg (cmolc dm^{-3})	0.77	1.81	1.12	0.37
Al+3 (cmolc dm^{-3})	0.02	0.03	0.07	0.53
H+Al (cmolc dm^{-3})	2.57	4.90	3.95	4.67
SB (cmolc dm^{-3})	1.79	4.25	2.93	0.67
CEC (cmolc dm^{-3})	4.36	9.15	6.88	5.33
SB (%)	40.97	46.64	42.62	12.14
m (%)	0.85	0.70	2.35	45.65
OXC (mg g^{-3})	0.74	1.84	1.45	0.64
TOC (g kg^{-1})	7.95	18.60	6.56	15.36

Legend: pH ($CaCl^2$); total nitrogen (TN); sulfur (S); phosphorus (P); potassium (K+); calcium (Ca); magnesium (Mg); exchangeable aluminum (Al+3); hydrogen + aluminum (H+Al); sum of bases (SB); base saturation (SB%); aluminum saturation (m%); oxidizable carbon (OCX) and total organic carbon (TOC). CLI = Integrated crop-livestock; LFI = Integrated livestock-forestry; Soybean-NT = soybean under reduced tillage; Native vegetation = area with Cerrado stricto sensu.

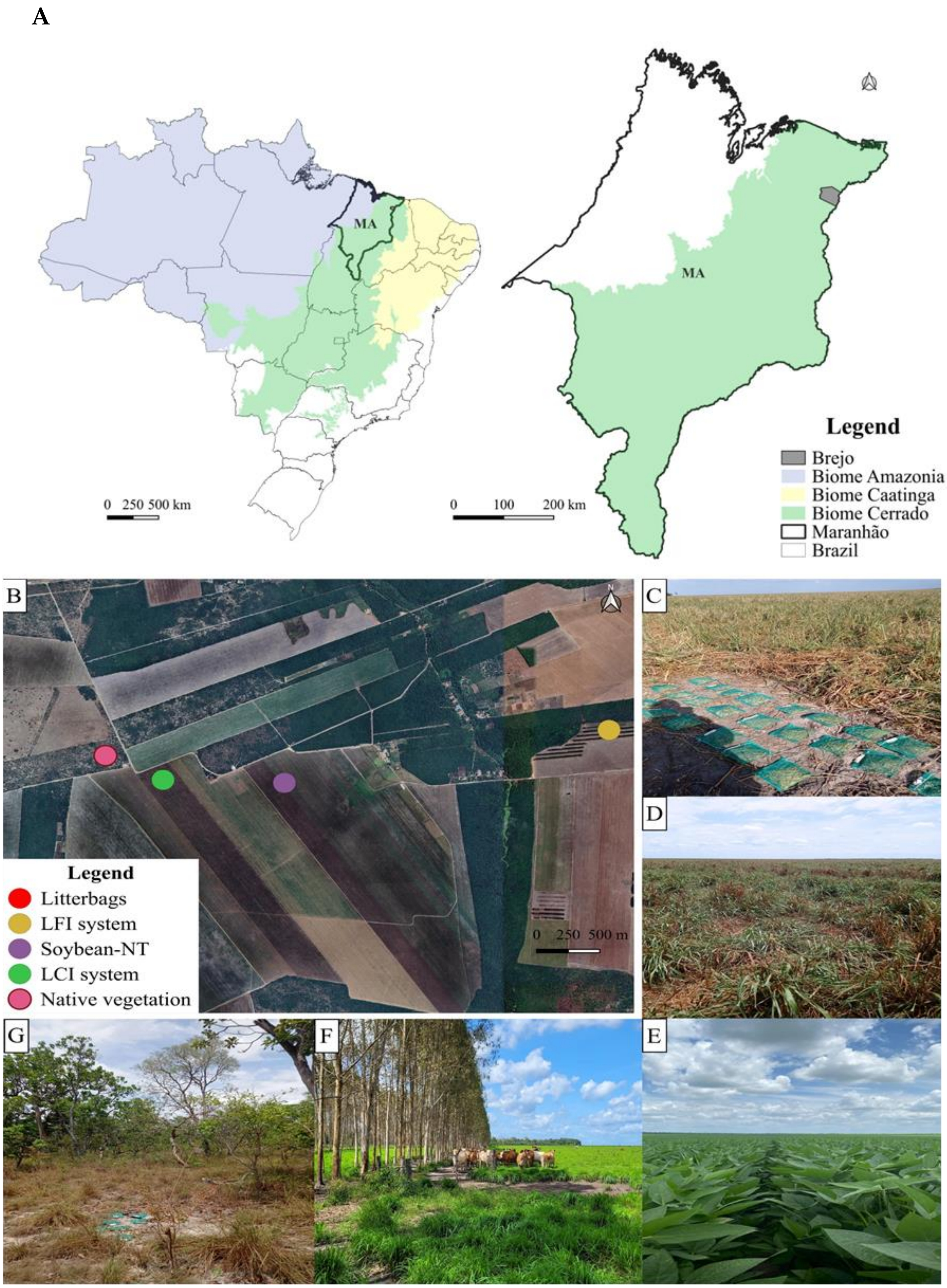

Figure 1. Location of the study area in Maranhão State, Brazil, highlighting the main biomes (Amazonia, Caatinga, and Cerrado) and the municipality of Brejo (**A**). Satellite image of the experimental farm showing the distribution of land use systems and litterbag installation sites (**B**). Field views showing litterbag installation (**C**), integrated crop–livestock system (LCI) (**D**), soybean under no-tillage (**E**), integrated livestock–forestry system (LFI) (**F**), and native vegetation (**G**).

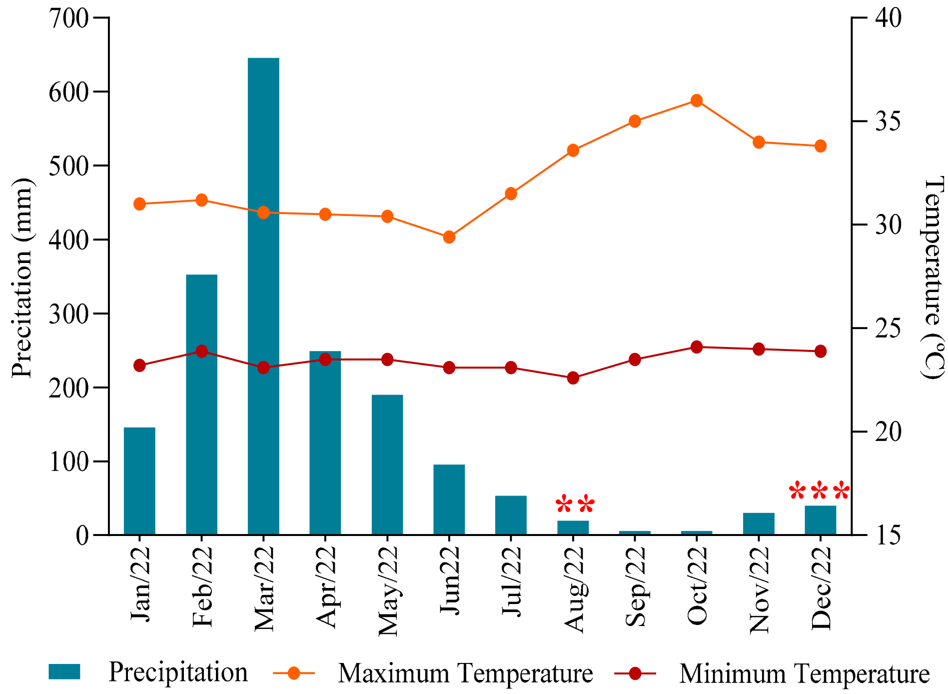

Figure 2. Mean precipitation values collected in the study area and maximum and minimum temperatures in 2022, from the INMET Meteorological Station, in Chapadinha, Maranhão, Brazil—(Station 82382). ** Start of the decomposition rate evaluation. *** End of decomposition rate evaluation.

2.2. Experimental Design

This study evaluated the decomposition of litter produced in different agricultural land use systems and in native vegetation of the Cerrado. Three agricultural systems were evaluated: (a) Integrated Crop–Livestock (ICL): Maize (*Zea mays*) intercropped with Marandu grass (*Urochloa brizantha* cv. Marandu); (b) Integrated Livestock–Forest (ILF): rows of Eucalyptus (*Eucalyptus grandis*) as the tree component, with Tamani grass (*Megathyrsus maximus* hybrid BRS Tamani) in the inter-rows; and (c) Soybean–NT in succession with millet: soybean (*Glycine max*) cultivation followed by millet (*Pennisetum glaucum*), under reduced tillage. In addition, an area under native Cerrado vegetation was included as a reference (control).

Plant residue and litter were collected on 29 July 2022, during the grain crop off-season. Sampling was performed using a 0.50 m^2 metal frame, randomly placed at two points in each land use system, following a methodology adapted from [31]. In the ILF system, collections were stratified into three distinct compartments: (i) eucalyptus litter collected within forest rows; (ii) Tamani grass sampled from the center of eucalyptus inter-row spaces; and (iii) mixed material (Eucalyptus + Tamani) collected from the transition zone between the canopy projection and the pasture. In the ICL system, residues were sampled from (iv) Soybean–NT and (v) Maize + Marandu intercropping, with the latter manually separated into its individual components: (vi) Maize and (vii) Marandu. As a reference, material from (viii) Native vegetation was also collected. All samples were oven-dried in forced air circulation at 65 °C to constant weight and subsequently weighed to determine dry mass, expressed in megagrams per hectare (Mg ha^{-1}).

2.3. Preparing Litterbags

Crop residue decomposition in different land use systems was evaluated using 0.20 × 0.20 m litterbags made from commercially available nylon nets with 2 mm mesh openings, obtained from local commercial sources (Teresina, PI; Brazil). The preparation of litterbags followed the methodology described by Vendramini, Dubeux, and Silveira [32].

Each litterbag was filled with 20 g of residues, previously oven-dried and cut into pieces of approximately 10 cm. Prior to placement of litterbags on the ground, the surface vegetation and plant debris were removed (Figure 1C). Each group of litterbags (collection times) was positioned on the ground 50 cm apart from each other. Eight treatments were evaluated, corresponding to different residue types: Soybean–NT, Marandu, Maize, Maize + Marandu, Eucalyptus, Tamani, Eucalyptus + Tamani, and Native vegetation. Each treatment had four replicates, with four collection times (0, 30, 60, and 118 days after litterbags placement in the field), totaling 128 litterbags. The evaluation period corresponded to the region's agricultural off-season, coinciding with the onset of soil preparation for the subsequent crop.

In the Integrated Crop–Livestock (ICL) system, litterbags were filled with residues originating from the mixture of the Maize + Marandu intercropping, Maize only, and Marandu only. The litterbags were placed on the soil at systematic points approximately 5 m apart, in the same system.

In the Integrated Livestock–Forest (ILF) system, litterbags were filled with eucalyptus residues (leaves and fine branches) and Tamani only, as well as with the Eucalyptus + Tamani mixture. To simulate natural deposition and decomposition patterns in the ILF system, litterbags containing only Eucalyptus residues were placed on the soil surface within the forest rows under the Eucalyptus tree canopy; those containing only Tamani residues were placed at the center of the inter-rows, outside the Eucalyptus canopy projection; and those containing the Eucalyptus + Tamani mixture were positioned at the canopy projection edge in the transition between tree rows and Tamani pasture. In each system, three groups (collection times) of 4 litterbags (replications; 12 in total) containing residues from the respective land use configuration were deployed. Litterbags containing residues from the Soybean-NT and the Native Cerrado vegetation were placed on the soil in their respective areas. A set of four litterbags for each type of residue was retained in the laboratory and considered as a control (time zero).

After each collection time (0, 30, 60, and 118 days), four litterbags per treatment (replicates) were retrieved. Samples were manually cleaned, rinsed in running water, and sequentially washed with distilled water, neutral detergent (0.1%), hydrochloric acid (0.3%), and finally distilled water again, following Boaretto et al. [33]. This thorough cleaning ensured the removal of soil and other impurities, while oven drying ensured accuracy in determining the residual dry matter. The material was dried in a forced-air oven at 65 °C until constant weight was achieved.

The percentage of residual dry matter (%RDM) was calculated as follows:

$$\%\text{RDM} = \left(\frac{\mathbf{Wf}}{\mathbf{Wi}}\right) \times \mathbf{100} \tag{1}$$

where

Wf = final dry weight (g);
Wi = initial dry weight (g).

Residual dry matter (RDM) was estimated considering the total litter, including leaves, branches, seeds, and bark, to characterize litterfall in the systems and native vegetation.

Source: Adapted from Olson [34] and Swift et al. [31].

The study aimed to simulate natural residue deposition in different land use systems (ICL, LFI, Soybean–NT, and Native vegetation), enabling the evaluation of decomposition over time and the interaction between residue types and the environmental conditions of each system.

2.4. Chemical Analysis and Chemical Characterization of Residues

Plant tissue samples remaining in the litterbags were ground in a Willey mill to pass through a 1 mm sieve and subsequently subjected to chemical analyses. At all collection intervals (0, 30, 60, and 118 days), total nitrogen (TN) content was determined using the Kjeldahl method [35], and organic C. was determined by the modified Walkley–Black method [36]. At 0 and 118 days, lignin (Lig) and cellulose concentrations were quantified using the acid detergent fiber (ADF) method of Van Soest and Wine [37]. At these same intervals, phosphorus (P), potassium (K^+), calcium (Ca), magnesium (Mg), and sulfur (S) concentrations were also measured. These elements were analyzed in the remaining biomass after nitroperchloric acid digestion: P by colorimetry, K^+ by flame photometry, Ca and Mg by atomic absorption spectrophotometry, and S by turbidimetry [38].

2.5. Decomposition Calculation

Residue decomposition was modeled based on the exponential equation proposed by Thomas and Asakawa [39]:

$$\mathbf{X} = \mathbf{X_0} \cdot \mathbf{e}^{-k\mathbf{t}} \tag{2}$$

where

X: is the amount of dry plant matter remaining after time t (days);
X_0: is the initial amount of dry plant matter or a given nutrient;
k: is the decomposition constant of the residue;
t: is the elapsed time (days).

From the value of k, the half-life ($T_{1/2}$) was calculated, which represents the time required for the decomposition of half the initial quantity of plant residues. This calculation was performed using the simple exponential linearization model proposed by Landsberg and Gower [40], according to the equation:

$$\mathbf{T_{1/2}} = \frac{\mathbf{0.69315}}{k} \tag{3}$$

Nutrient release during the 118-day straw decomposition period was quantified using the following Equation (4) [1].

$$\mathbf{N_{released}} = \mathbf{C_{Nutrient}} \times \mathbf{M_{Straw}} \times \mathbf{10} \times \mathbf{R_{release}} \tag{4}$$

where

$N_{released}$ = Reased nutrient (kg ha^{-1});
$C_{nutrient}$ = Nutrient content in the straw (g kg^{-1});
M_{straw} = Straw mass (t ha^{-1});
10 = Coversion factor from t g ha^{-1} to kg ha^{-1}.

In parallel, organic C. and nitrogen (N) accumulation were evaluated by multiplying the initial dry mass (20 g) by their respective concentrations at each collection time. Results were expressed as a percentage relative to the initial value (time zero = 100%). Decomposition dynamics were modeled using non-linear approaches, with parameters estimated by dynamic curve fitting. The model showing statistical significance ($p < 0.05$) and the highest coefficient of determination (R^2) was selected. This integrated methodology enabled characterization of both quantitative nutrient release and decomposition kinetics throughout the experimental period.

2.6. Data Analysis

Data were first examined for outliers using the boxplot technique. Mean values of each plant residue type were compared following the method of Payton, Miller, and Raun [41], using 95% confidence intervals (CIs). Significant differences between treatments were considered when upper and lower limits of the CIs did not overlap.

Correlations between variables were determined using principal component analysis (PCA) and cluster analysis, both performed in R (R Core Team, 2017). All variables were standardized prior to multivariate analysis [42]. All data processing and visualization were conducted using R (version 3.5.2) with the ExpDes and tidy verse packages [43,44], and visualizations were created in Microsoft Excel 2019 [45].

3. Results

The Eucalyptus + Tamani and Maize + Marandu residues had the highest dry matter accumulation in the soil, with 16.21 Mg ha^{-1} and 16.05 Mg ha^{-1}, respectively. These values represent an increase of approximately 276% compared to Native Cerrado vegetation (4.28 Mg ha^{-1}) and were also greater than those recorded for the Soybean–NT and Tamani systems alone (Figure 3).

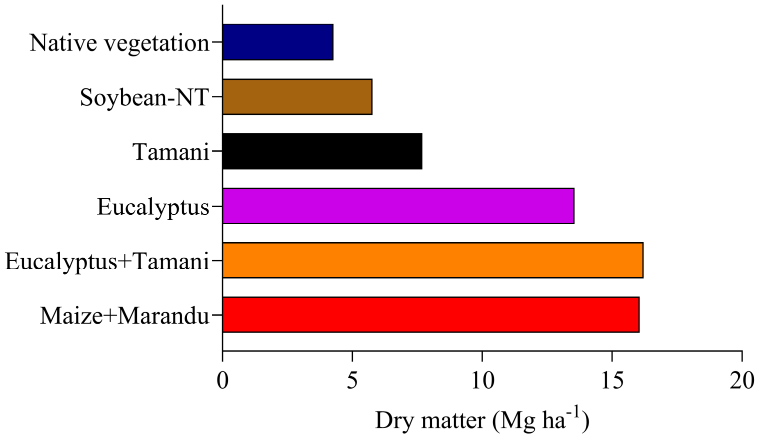

Figure 3. Dry matter production of straw and litter from agricultural, forage, and tree components in different land use systems in the Cerrado of Northeastern Brazil. Brejo, Maranhão state.

Carbon contents varied significantly among the residues analyzed (Figure 4A). Eucalyptus had the highest C concentration (43%), statistically equivalent to Eucalyptus + Tamani (41%). However, Eucalyptus differed significantly ($p < 0.05$) from all other treatments: Maize + Marandu (40%), Maize (39%), Tamani (40%), Soybean–NT (39%), Marandu (37%), and Native vegetation (37%).

Across all plant residues, the general trend in macronutrient concentrations was: N > Ca > K > Mg > P > S (Figure 4). Marandu and Soybean–NT residues had the highest N (37.8 and 39.2 g kg^{-1}, respectively), P (2.42 and 2.37 g kg^{-1}, respectively), and Mg (2.38 and 2.83 g kg^{-1}, respectively) contents. In contrast, Eucalyptus + Tamani and Eucalyptus residues contained the highest Ca concentrations (6.72 and 6.11 g kg^{-1}, respectively), while K+ was highest in Marandu (52.26 g kg^{-1}). Sulfur content showed little variation among residues, with the lowest values in Maize and Native vegetation (9.46 and 1.09 g kg^{-1}, respectively).

Eucalyptus, Eucalyptus + Tamani, and Native vegetation residues showed the highest lignin concentrations (20% to 30%) and lowest cellulose contents, indicating greater recalcitrance to decomposition. The Lig/N ratio was also highest in these residues, suggesting greater resistance to microbial degradation. The C/N ratio was greater than 25 in all residues, indicating low initial N availability, which may negatively influence the residue decomposition rate.

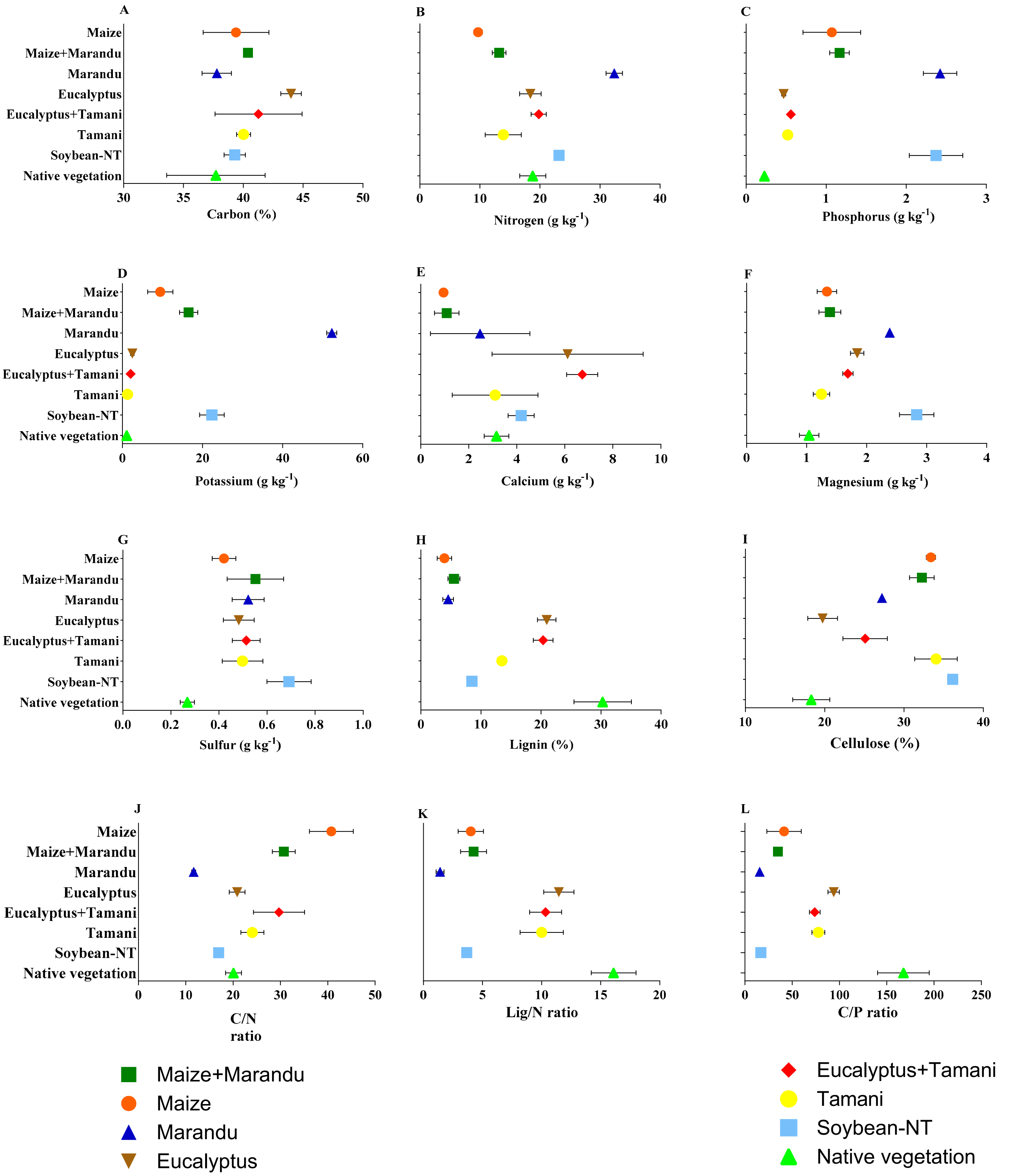

Figure 4. Initial concentrations of carbon (**A**), nitrogen (**B**), phosphorus (**C**), potassium (**D**), calcium (**E**), magnesium (**F**), sulfur (**G**), lignin (**H**), cellulose (**I**), C/N ratio (**J**), Lig/N (**K**) and C/P (**L**) of different plant residues in different land use systems in the Cerrado of Northeastern Brazil. Brejo, Maranhão state. Error bars correspond to confidence intervals ($p < 0.05$).

The dynamics of losses in dry matter (DML), C, and N were adequately described by exponential decay models for all analyzed plant residues (Figure 5). There were large differences in litter decomposition dynamics in response to the management system and plant residue characteristics. The litter decomposition rate (k) ranged from 0.0041 to 0.0018

(Table S2), corresponding to the resistant fraction of dry matter (RDM%), composed of slowly degrading compounds such as lignin and cellulose, which accounted for 59–79% of the biomass. The active fraction, made up of rapidly decomposing substances, represented 21–41% of the biomass (Figure 5A).

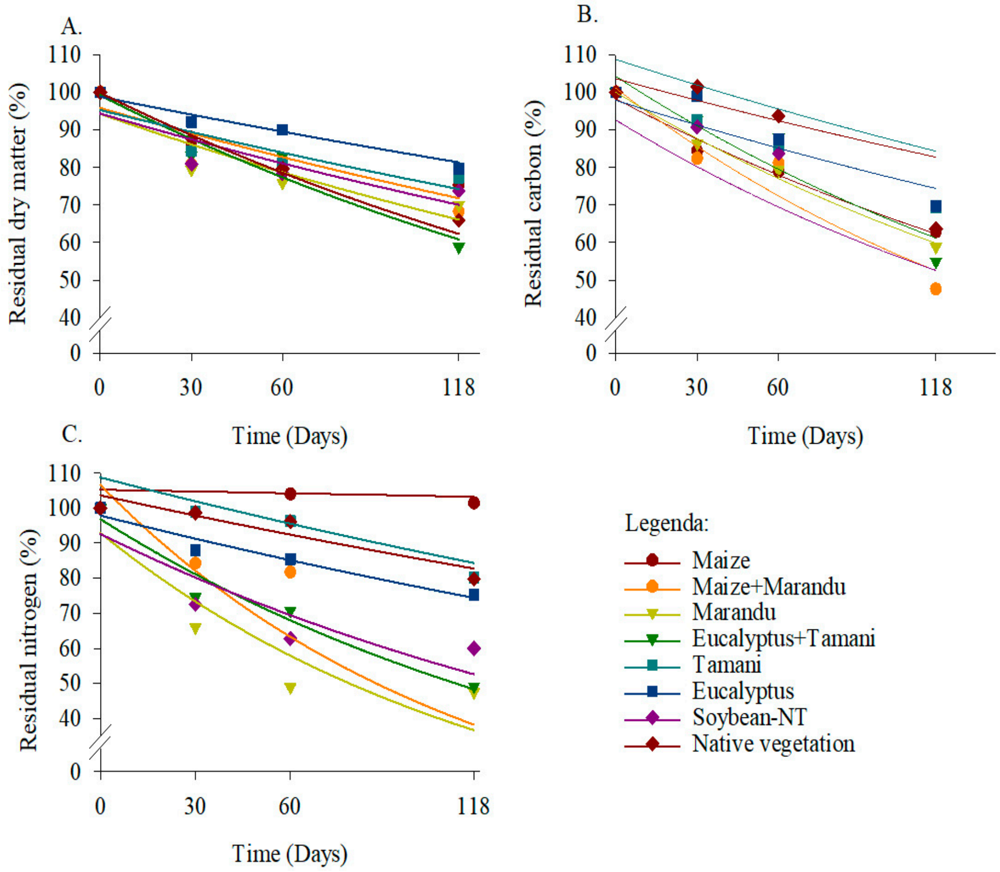

Figure 5. Residual dry matter (%) (**A**), carbon (%) (**B**), and nitrogen (%) (**C**) in different residues of agricultural, forage, and tree components after 118 days of litterbag placement in the Cerrado of Northeastern Brazil. Brejo, Maranhão state. The points represent the observed values, and the lines represent the values fitted to the regression equation.

The highest active (decomposable) fraction was observed in the Eucalyptus + Tamani residues, indicating greater susceptibility of this mixture to decomposition. In contrast, Eucalyptus alone, originating from the same ILF system, had the lowest active fraction and the longest half-life (385 days), demonstrating marked differences in decomposition rates between these materials.

For residual N, the lowest values at 118 days after litterbag placement were found in Maize + Marandu (21%) and Marandu (48%) residues, which exhibited the highest decomposition rates (0.0086 and 0.0079 day^{-1}, respectively) and the shortest half-lives (81 and 88 days, respectively). In contrast, Maize straw showed no significant change in N release, although an 11% increase was recorded at 30 days and persisted over 118 days (Figure 5C).

For residual C, the decreasing order of decomposition rate was Maize + Marandu > Eucalyptus + Tamani > Marandu > Maize > Soybean–NT > Native vegetation > Eucalyptus = Tamani. Eucalyptus and Tamani residues had the lowest C loss (31%) and the highest T1/2 after 118 days of decomposition (Figure 5B, Table S2).

Nutrient release patterns also varied markedly among residues. The Eucalyptus + Tamani mixture, with an initial dry mass of 16.214 Mg ha^{-1}, released on average 121.08 kg ha^{-1} of N and 257.75 kg ha^{-1} of C, along with P (2.41 kg ha^{-1}), K+ (16.01 kg ha^{-1}), Ca (17.94 kg ha^{-1}), Mg (4.93 kg ha^{-1}), and S (2.37 kg ha^{-1}). These values partly reflect the substantial litter contribution from both species in this system, enhancing nutrient cycling efficiency compared to the other residues (Table 2).

Table 2. Nutrients released during the decomposition of plant residues 118 days after litterbags placement in different litter types and land use systems in the Cerrado of Northeastern Brazil. Brejo, Maranhão, Brazil.

Litters	C	N	P	K	Ca	Mg	S
	kg ha^{-1}						
Maize + Marandu	150.13	22.12	3.61	32.67	2.07	3.66	3.47
Eucalyptus + Tamani	256.96	121.08	2.41	16.01	17.94	4.93	2.37
Tamani	67.71	32.63	0.79	4.11	2.12	1.12	1.16
Eucalyptus	115.71	46.98	2.31	6.63	10.49	2.81	0.98
Soybean-NT	51.92	30.16	1.58	11.22	2.69	2.22	1.89
Native vegetation	54.26	33.87	0.51	3.59	2.76	1.14	0.75

Legend: C: Carbon; N: Nitrogen; P: Phosphorus; K+: Potassium; Ca: Calcium; Mg: Magnesium; and S: Sulfur.

Maize + Marandu stood out for its high K^+ release rate (32.67 kg ha^{-1}). Eucalyptus alone showed elevated N (46.98 kg ha^{-1}) and Ca (10.49 kg ha^{-1}) release rates. Tamani grass provided a moderate N supply (32.63 kg ha^{-1}) but released lower amounts of P, K^+, and S, reflecting slower decomposition. Native vegetation had the lowest nutrient cycling potential from litter, with only 0.51 kg ha^{-1} of P and 0.75 kg ha^{-1} of S.

Principal component analysis (PCA) accounted for 78.1% of the total variance, with 51.7% explained by principal component 1 and 26.4% by principal component 2 (Figure 6). Residues from the Maize + Marandu and Eucalyptus + Tamani intercropping systems displayed a distinct pattern compared to other systems, showing positive loadings on principal component 1, opposite to the trend observed in the remaining residues. The Eucalyptus + Tamani system was associated with the highest decomposition rate and greater N, C, Ca, and Mg contents, whereas Maize + Marandu was linked to the highest P, K^+, and S contents. Native vegetation, in turn, was associated with the highest lignin concentrations.

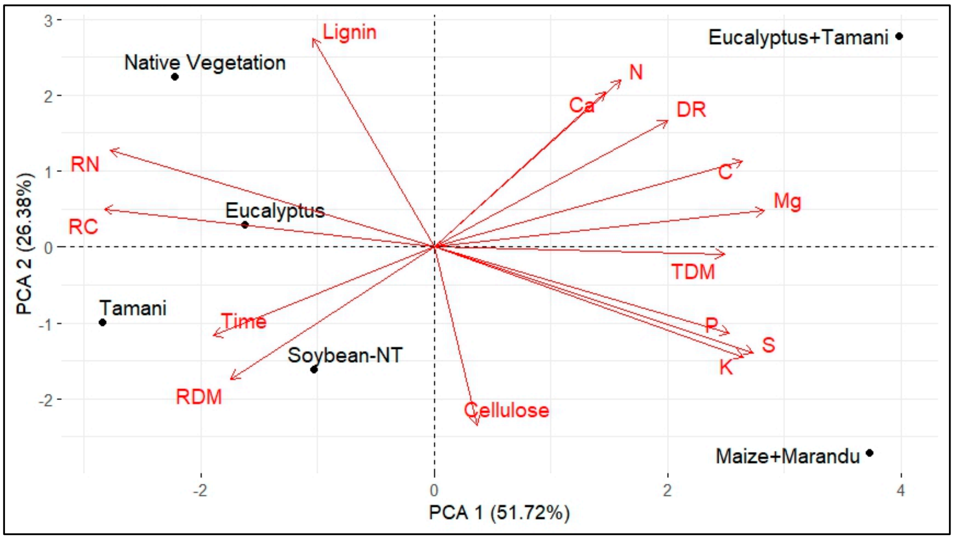

Figure 6. Residual dry matter (RDM), residual carbon (RC), and residual nitrogen (RN) in residues of agricultural, forage, and tree components subjected to different conservation systems after 118 days of decomposition. Parameters evaluated: half-life (T½), decomposition rate (k), initial total dry mass (TDM), chemical composition (C, N, P, K^+, Ca, Mg, and S), and fibrous components (cellulose and lignin) in the Cerrado of Northeastern Brazil. Brejo, Maranhão state.

4. Discussion

The Eucalyptus + Tamani and Maize + Marandu residue combinations exhibited synergistic effects on decomposition, as demonstrated by the decomposition constant and further supported by principal component and cluster analyses. These effects were driven by stoichiometric complementarity (cellulosic vs. non-cellulosic C/N) and the coordinated activity of diverse decomposer microorganisms [14,43]. This pattern, consistent with the metabolic balance theory [44], enhanced the efficiency of extracellular hydrolases (e.g., cellulases, peroxidases), thereby accelerating C and N mineralization via preferential aerobic pathways. Moreover, the structural heterogeneity of mixed litter promoted ecological succession among decomposer communities [45,46].

In this study, the areas under ILF and ICL systems were both managed under rotational cattle grazing in paddocks with a stocking rate of 2.5 AU ha^{-1}. Each paddock was occupied by the animals for 29 days in ICL and 4 days in ILF. Thus, grazing history significantly influenced decomposition by altering soil physicochemical properties (Table 1, full historical data are provided in Supplementary Table S1), supporting the initial hypothesis of this study. These effects occur primarily through: (i) the physical redistribution of plant residues, which increases the specific surface area available for microbial action [47]; and (ii) changes in C/N ratio of residual litter due to grazing selectivity, thereby modifying mineralization rates [1,48]. These findings suggest that different processes may regulate microbiota–plant interactions in landscapes with distinct management systems, or that the efficiency of these interactions varies according to the management system adopted [49].

Despite the high initial N and P concentrations in Soybean–NT residues and the low C/N and Lig/N ratios in Marandu residues, their decomposition rates were slower than those of Eucalyptus + Tamani residues. This indicates that, regardless of residue quality, the adoption of consolidated management practices with a continuous animal component, such as in the ILF system, is the primary driver of residue decomposition rates. Continuous system management without soil disturbance favors the selection of specialized microorganisms [50]. The stability of microbial communities in such environments, in turn, promotes more efficient decomposition across a range of substrates [51]. Conversely, in systems such as Soybean–NT and even ICL, microbial community composition is influenced by the seasonal pattern of grain cultivation and by continuous microbial inoculation processes, such as nitrogen-fixing bacteria in soybean cultivation [7], which modulate the structure and function of soil microbial communities [4]. Overall, the results of this study demonstrate that the temporal stability of management systems is a key determinant of plant residue decomposition processes in the soil.

Equally important as the residue decomposition rate and the amount of residual material are the C and N release rates over time. The faster decomposition observed during the initial stages can be attributed to the high content of labile compounds such as sugars, amino acids, and proteins [52]. Consequently, C quality in the residue, the presence of water-soluble compounds, and lignin content influence decomposer activity more strongly than initial nutrient concentrations [50]. In later stages, decomposition and nutrient release rates typically decline due to the higher proportion of recalcitrant components, such as lignin and cellulose, remaining in the material [53].

The greater proportional release of C and N compared to dry matter loss in Maize + Marandu residues observed in this study is unusual in decomposition studies [14,15,54,55]. This pattern likely resulted from the combination of favorable environmental conditions, high residue quality, and specific management practices. Initial concentrations of N, P, lignin, and the Lig/N and C/N ratios were associated with higher percentages of C and N release, highlighting the importance of these factors in nutrient release dynamics in tropical ecosystems [56,57].

Previous studies in the region [6] have shown that N release rates vary according to residue composition, which is higher in millet + brachiaria intercroppings (C/N ≈ 25) and lower in millet monoculture (C/N ≈ 40) due to lower initial N concentrations and slower dry matter decomposition. These results are consistent with the central role of C/N ratio in nutrient release dynamics [55]. In the present study, N release from maize residues (C/N ≈ 45) followed the three-phase model described by Berg and Staaf [58]: (i) rapid mineralization of soluble fractions (5-15% of total N), (ii) microbial immobilization (30–100 days), and (iii) gradual release through microbial turnover. This pattern reflects the biochemical characteristics of maize straw—high cellulose content (35-45% DM) and low initial N (0.6–0.8% DM), which promote temporary microbial immobilization of N before its subsequent release [59].

The study revealed distinct patterns in potassium and phosphorus (P) release during plant residue decomposition. Potassium was characterized by rapid release, with more than 80% becoming available within the first 118 days, regardless of the management system. This accelerated dynamic can be attributed to: (i) the predominance of K^+ in soluble forms (~90% of the total), (ii) its localization in the cytosol, and (iii) its high mobility during leaching, traits that make it immediately available for physiological processes such as osmoregulation and enzyme activation [60].

In contrast, P exhibited the slowest release rate, with patterns strongly linked to the C/P ratio of the residues. For instance, Soybean–NT (C/P = 16.8) mineralized 40% of its P, whereas residues with C/P > 30, such as Maize + Marandu, released only 15%. This difference reflects two key processes: (i) greater microbial immobilization in residues with high C/P ratios and (ii) dependence on the hydrolysis of organic compounds for P availability. Low rainfall rates during the experimental period (18.1 mm month^{-1}; August–December) further constrained P release, as indicated by the reduced decomposition constants (k = 0.0041–0.0018) [61,62].

These results align with previous studies [63,64], confirming that P availability is intrinsically linked to soil and climate conditions. In both the ILF system and native vegetation, low initial P content in the litter, combined with the presence of immobilizing compounds, underscored the combined influence of residue C/P ratio and climatic factors on P dynamics [65]. Overall, these findings highlight the need to account for nutrient-specific characteristics when evaluating decomposition processes and nutrient cycling in agricultural systems.

These distinct patterns have clear practical implications: K^+ management should focus on strategies that capitalize on its rapid availability, particularly under stressed conditions, whereas P management requires the use of residues with a low C/P ratio or additional supplementation in systems with high microbial demand. The results reinforce that residue quality, expressed through parameters such as the chemical form of K^+ and C/P ratio, is the primary factor regulating nutrient cycling efficiency in tropical systems.

The findings also indicate that the set of practices associated with ICL and Soybean–NT systems, characterized by reduced soil disturbance, the use of cover crops, and the application of mineral inputs, can promote the maintenance and accumulation of Ca and Mg. As noted by Rebêlo et al. [66], the elevated Mg levels in grain cultivation systems may be linked to the presence of legumes such as soybeans. These species play a crucial role in conservation agriculture by enriching litter with nutrients, which in turn supports the development and stability of soil biological communities, creating a positive feedback loop [67,68].

Nutrient release from litter follows a characteristic sequence, with Ca being one of the last macronutrients to be released [69]. Thus, the results of this study provide important insights into the effects of soil management under tropical conditions in Brazil, particularly regarding decomposition processes and nutrient cycling. In tropical ecosystems, improving soil chemical and biological properties is closely linked to the adoption of cover crops, whether through overseeding or intercropping strategies.

Understanding the mechanisms governing plant residue decomposition is essential for agricultural planning, as it supports the strategic selection of species for inclusion in production systems. The results indicate that, under the soil and climatic conditions of the Cerrado in Northeastern Brazil, C and N release rates are strongly influenced by the initial quality of the residues, particularly lignin content and C/N ratio, which have proven to be reliable predictors of their release dynamics.

Although this study did not evaluate the interactive effects between management practices and residue quality on C and N decomposition and release rates, such interrelationships warrant priority in future research to optimize strategies for maintaining soil fertility in these ecosystems.

5. Conclusions

Agricultural management practices that ensure the temporal stability of production systems, such as ILF, are the primary drivers of plant residue decomposition. In contrast, intensive management combined with crop seasonality in grain production systems constrains the decomposition of plant residues, even under sustainable approaches such as Integrated Crop–Livestock (ICL) systems. The decomposition of plant residues is particularly influenced by lignin content, the C/N ratio, and the structural diversity of mixed litter. Residue combinations, such as Eucalyptus + Tamani and Maize + Marandu, enhanced C and N mineralization through stoichiometric complementarity and the coordinated activity of diverse decomposer microorganisms.

Our study provides evidence that residue mixtures with complementary traits under reduced soil disturbance can optimize nutrient cycling and soil fertility. Finally, our findings demonstrate that the adoption of practices that include perennial components of integrated systems (e.g., pasture and trees) combined with temporal stability is a key aspect for nutrient cycling intensification and can be recommended for sustainable agriculture in the Cerrado of Northeast Brazil.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy15122687/s1. Table S1: Land use and management history systems evaluated in the study. Brejo, Maranhão state, Brazil; Table S2: Nonlinear model parameters adjusted for dry matter and nutrients (N and C) during field exposure of different plant residues in land use systems in the Cerrado of northeastern Brazil. Brejo, Maranhão. References [23,70,71] are cited in the supplementary materials.

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