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Straw production and nutrient cycling in different cover crops under sole and mixed cropping systems

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ABSTRACT

This study aimed to evaluate the production, decomposition, and nutrient cycling of the residues of cover crops grown in isolation and consortium, in areas of transition and maintenance of the no-till system in the Cerrado. Two studies were conducted simultaneously in a randomized block design, in which the following ground covers were evaluated: 1) *Urochloa* spp.; 2) Pearl millet; 3) Slenderleaf rattlebox (*Crotalaria ochroleuca*); 4) Consortium 1 (C1): *Urochloa* spp., Pearl millet, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*Crotalaria breviflora*), Buckwheat, Finger millet and Crambe; 5) Consortium 2 (C2): *Urochloa* spp., Pearl millet, Finger millet, Forage sorghum, Cowpea, and Pigeon pea; 6) Consortium 3 (C3): *Urochloa* spp., Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*C. breviflora*), Buckwheat, Finger millet and Crambe, with four replications. The dry matter (DM), decomposition, and nutrient cycling of the cover residues were evaluated. The DM production was higher in all the maintenance phase covers except C3. The highest decomposition rate and lowest T½ life of the residues occurred in Slenderleaf rattlebox (49.6% and 17 days) in the transition phase and *Urochloa* spp. (48.6% and 24 days) and C3 (48.5% and 24 days) in the maintenance phase, respectively. The greatest accumulation of nutrients in the transition phase occurred in C3 for N, P and Mg, in C2 for K, and in C1 for Ca and S, while in the maintenance phase, the greatest accumulation of N, P, K, Mg, and S occurred in C1, and Ca occurred in Pearl millet. The accumulated K, P, and S levels in the plant residues were cycled more quickly into the soil in all the covers evaluated in the transition and maintenance phases. Residue decomposition and nutrient cycling are higher in the maintenance phase than in the transition phase.

Keywords: Soil conservation, Cover crops, Plant residues, Plant mixtures.

Produção de palha e ciclagem de nutrientes em diferentes coberturas sob cultivo isolado e consórcios

RESUMO

O objetivo deste estudo foi avaliar a produção, a decomposição e a ciclagem de nutrientes dos resíduos das plantas de cobertura em cultivo isolado e em consórcio, em áreas de transição e manutenção do sistema de plantio direto no cerrado. Dois estudos foram conduzidos simultaneamente no delineamento de blocos ao acaso, em que foram avaliadas as coberturas do solo: 1) Braquiária; 2) Milheto; 3) Crotalária (*Crotalária ochroleuca*); 4) Consórcio 1 (C1): Braquiária, Milheto, Crotalária (*C. ochroleuca*), Crotalária (*Crotalária breviflora*), Trigo mourisco, Capim-coracana e Crambe; 5) Consórcio 2 (C2): Braquiária, Milheto, Capim-coracana, Sorgo forrageiro, Feijão-caupi e Feijão-guandu; 6) Consórcio 3 (C3): Braquiária, Crotalária (*C. ochroleuca*), Crotalária (*C. breviflora*), Trigo mourisco, Capim-coracana e Crambe, com quatro repetições. Avaliou-se a seca (MS), a decomposição e a ciclagem de nutrientes dos resíduos das coberturas. A produção de MS foi superior em todas as coberturas na fase de manutenção, exceto no C3. A maior taxa de decomposição e o menor T½ vida dos resíduos ocorreram na crotalária (49,6% e 17 dias) na fase de transição e na braquiária (48,6% e 24 dias) e no C3 (48,5% e 24 dias) na fase de manutenção, respectivamente. O maior acúmulo de nutrientes na fase de transição ocorreu no C3 para N, P e Mg, no C2 para K e no C1 para o Ca e S, enquanto na fase de manutenção, ocorreu maior acúmulo de N, P, K, Mg e S no C1, e de Ca ocorreu no milheto. Os teores acumulados de K, P e S nos resíduos das plantas foram ciclados mais rapidamente para o solo em todas as coberturas avaliadas nas fases de transição e manutenção. A decomposição dos resíduos e a ciclagem de nutrientes são mais elevadas na fase de manutenção do que na de transição.

Palavras-chave: Conservação do solo, Plantas de cobertura, Resíduos vegetais, Mistura de plantas.

1. Introduction

No-till farming is a conservation management system that has evolved over the last decades and has become one of the most modern sustainable agricultural production systems for the Brazilian Cerrado (Mazetto Júnior et al., 2019).

Minimal soil disturbance restricted to the planting row, crop rotation, and the maintenance of crop residues on the soil surface promotes a continuous input of organic matter, leading to significant changes in the soil physical, chemical, and biological attributes as cropping cycles progress. This, in turn, favors plant development and can increase the productivity of crops grown in succession (Loss et al., 2019; Pinto et al., 2022; Torres et al., 2024; Boldrin et al., 2024).

However, these principles are not always followed in the Brazilian Cerrado, mainly due to the lack of crop rotation during the dry season. During this period, monocropping or simple crop succession often predominates, resulting in insufficient soil cover with plant residues because of the low production of remaining dry matter (Passos et al., 2018).

Several studies have been conducted in search of cover crops that are better adapted to the edaphoclimatic conditions of the Cerrado region and that can be grown either preceding or in succession to the main crop (Pacheco et al., 2017a; Boyer et al., 2018; Loss et al., 2019; Torres et al., 2021; Pinto et al., 2022), producing high-quality residues in sufficient quantities to ensure soil cover during the off-season (Silveira et al., 2021).

Among the most commonly used plants for biomass production in the Brazilian Cerrado, Urochloa species, Pearl millet, Slenderleaf rattlebox, and mixtures of these three species in the same area have shown the best performance (Ferreira Júnior et al., 2023). These plants are resilient and grow well during the dry season, producing large amounts of plant residues that protect the soil from erosion while recycling considerable amounts of nutrients, resulting in significant benefits to the production system and crop yields (Pacheco et al., 2017a; Pinto et al., 2023; Torres et al., 2024).

However, a new variable has been introduced into the production systems used in the Brazilian Cerrado: cover crop seed mixtures, with up to eight different species sown in the same area. Theoretically, these mixtures are promising because it is possible to combine seeds to achieve multiple objectives, such as controlling nematodes, weeds, pests, and diseases, in addition to enhancing nutrient cycling as previously mentioned. Nevertheless, it is still unclear whether these goals are truly achieved (Silva et al., 2021), as there is limited scientific information on this topic in the literature, which needs further evaluation.

Regarding nutrient cycling, some studies have shown that *Brachiaria* species, Pearl millet, *Crotalaria* spp., and their mixtures contribute considerable amounts of organic matter to the soil. The cycling of nutrients (N, P, K, Ca, Mg, and S) from plant residues occurs at different rates, being slower during the dry season and faster during the rainy season (Torres and Pereira, 2008; Torres et al., 2021).

Under both conditions, N and K are the nutrients most rapidly cycled within the first 30 days after management (Pacheco et al., 2017b) due to their high mobility in the soil. However, little is known about the advantages of mixtures containing more than three plant species in this region (Silveira et al., 2021).

Given this context, the hypothesis tested in this study was that cover crop mixtures may produce greater fresh and dry biomass and accumulate and cycle more nutrients than sole cover crops in no-till areas. This study aimed to evaluate the production, decomposition, and nutrient cycling of cover crop residues grown as sole crops or mixtures, in areas transitioning to and maintaining no-till systems in the Cerrado region of Minas Gerais.

2. Material and Methods

The study was conducted in the municipality of Uberaba, Minas Gerais, in an experimental area located at 19°39'10.17" S latitude and 47°58'15.65" W longitude, at an altitude of approximately 800 m, from November 2023 to February 2024.

The soil in the cultivation areas was classified as Oxisol (Santos et al., 2018), with a sandy loam texture and gently undulating topography. In the transition area, at a depth of 0-0.20 m, the following physical and chemical attributes were observed: 210 g kg^{-1} of clay, 710 g kg^{-1} of sand, and 80 g kg^{-1} of silt; pH ($CaCl_2$) of 5.1; 28.1 mg dm^{-3} of P (resin); 2.76 $mmol_c$ dm^{-3} of K^+; 13.9 $mmol_c$ dm^{-3} of Ca^{2+}; 2.8 $mmol_c$ dm^{-3} of Mg^{2+}; 24 $mmol_c$ dm^{-3} of H^+ Al; base saturation (V) of 44.7%; 12.6 g dm^{-3} of organic matter; and a cation exchange capacity (CEC) of 43.45 $mmol_c$ dm^{-3}.

In the area under the maintenance phase of the no-till system (NTS), at a depth of 0-0.20 m, the following physical and chemical attributes were observed: 210 g kg^{-1} of clay, 710 g kg^{-1} of sand, and 80 g kg^{-1} of silt; pH ($CaCl_2$) of 5.0; 43.8 mg dm^{-3} of P (resin); 1.63 $mmol_c$ dm^{-3} of K^+; 9.4 $mmol_c$ dm^{-3} of Ca^{2+}; 2.6 $mmol_c$ dm^{-3} of Mg^{2+}; 26 $mmol_c$ dm^{-3} of H^+ Al; base saturation (V) of 34.3%; 13.7 g dm^{-3} of organic matter; and a cation exchange capacity (CEC) of 39.61 $mmol_c$ dm^{-3}.

According to the soil analysis results, it was necessary to correct soil acidity by applying 500 kg ha^{-1} of dolomitic limestone (ECCE: 63%) on the soil surface in a split application, 60 days before the establishment of the experiment.

Two experiments were conducted simultaneously in areas at different stages of no-till system (NTS) implementation: one in a transition phase area (9 years under NTS) and another in a maintenance phase area (23 years under NTS), using different cover crops grown either as sole crops or in mixtures.

In both areas, the experimental design used was a randomized block design, evaluating six different soil cover treatments: 1 - Brachiaria (*Urochloa ruziziensis*); 2 - Pearl millet (*Pennisetum glaucum* L.); 3 - Slenderleaf rattlebox (*Crotalaria ochroleuca*); 4 - Consortium 1: Brachiaria, Pearl millet, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*Crotalaria breviflora*), Buckwheat (*Fagopyrum esculentum*), Finger millet (*Eleusine coracana*), and Crambe (*Crambe abyssinica*); 5 - Consortium 2: Brachiaria, Pearl millet, Finger millet, Forage sorghum (*Sorghum bicolor* L.), Cowpea (*Vigna unguiculata*), and Pigeon pea (*Cajanus cajan*); 6 - Consortium 3: Brachiaria, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*C. breviflora*), Buckwheat, Finger millet, and Crambe, with four replications.

Both areas contained 24 plots each, totaling 48 plots in the experiment, each measuring 32 m² (8 m × 4 m).

Before sowing the cover crops, the area was desiccated for weed control using a non-selective systemic herbicide with glyphosate as the active ingredient (4.0 L ha^{-1}), a selective systemic herbicide based on 2,4-D (1.5 L ha^{-1}), and a systemic herbicide based on clethodim (0.40 L ha^{-1}).

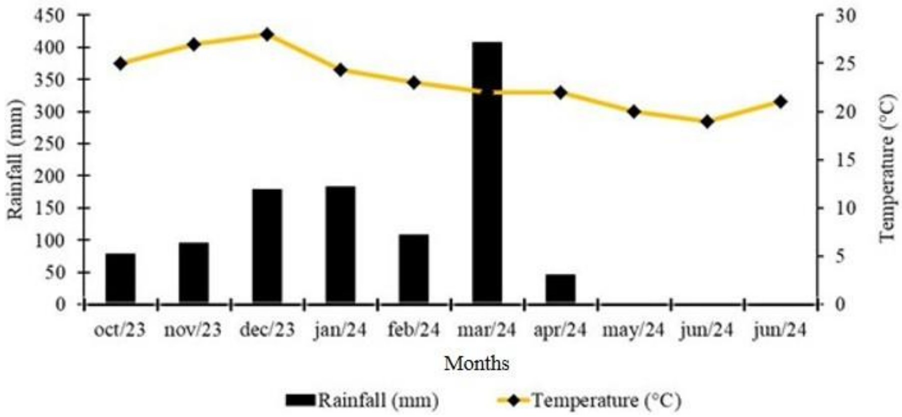

Figure 1. Cumulative rainfall and average monthly temperature from October 2023 to July 2024, obtained from the Meteorological Database for Teaching and Research of INMET (2024).

The cover crops were sown mechanically at the beginning of November 2023 using a Semina brand seeder, model 2, with five rows spaced 0.20 m apart. Sowing densities were 25, 50, and 50 seeds per meter for *Crotalaria* spp., Brachiaria, and Pearl millet, respectively, and 22.5 kg ha^{-1} for mixtures 1, 2, and 3. When 50% of these plants reached full flowering, approximately 100 days later (early February 2025), samples were collected to evaluate fresh and dry biomass within a 2 m² area of each plot. The fresh material was weighed, then taken to the laboratory and dried in a forced-air oven at 65 °C for 72 hours or until reaching constant weight, after which it was weighed again and the results expressed in Mg ha^{-1}.

The litterbag method was used to evaluate the decomposition rate and nutrient release, with bags made of 2 mm mesh and measuring 0.30 × 0.30 m (Santos and Wilfort, 1981). 192 bags were placed on the soil surface, each containing 30 g of plant residues. Sampling was conducted 15, 30, 60, and 90 days after the bags were placed in the field. After collection, the plant residue from each bag was cleaned over a 0.053 mm mesh sieve, dried in a forced-air oven at 65 °C until reaching constant weight, and then ground.

These ground residues were then taken to the chemical analysis laboratory to determine the concentrations of N, P, K, Ca, Mg, and S to assess nutrient cycling, following the methodologies proposed by Teixeira et al. (2017). To describe the decomposition of plant residues, the exponential mathematical model described by Thomas and Asakawa (1993) was applied, expressed as $X = X_0e^{-kt}$, where X is the amount of remaining dry mass after a while t (in days); X_0 is the initial amount of dry mass or nutrient; and k is the residue decomposition constant.

The data were subjected to tests for normality, homogeneity of variances, and block additivity using the Shapiro-Wilk and Bartlett tests, respectively. Subsequently, the data were analyzed separately through analysis of variance (ANOVA) using the F-test, and when significant, means were grouped using the Scott-Knott test ($p< 0.05$). A combined analysis of variance for the two experimental areas was then performed using the Agroestat software, developed by Barbosa and Maldonado Júnior (2009).

Regression analysis and the mathematical equations described in the applied model were used to evaluate the decomposition rate and nutrient cycling, with all calculations performed using SigmaPlot software, version 10.

3. Results and Discussion

Analyzing the dry matter (DM) production in the areas under the transition and maintenance phases of the no-till system (NTS), it was observed that, among the sole cover crops, Pearl millet showed the highest values ($p < 0.05$), with 10.99 and 13.32 Mg ha^{-1}. Among the mixed cropping systems, consortium 1 (C1) and 2 (C2) stood out, with 15.38 and 17.93 Mg ha^{-1}, respectively (Table 1).

Regarding DM production between the transition and maintenance phases, significant differences ($p < 0.05$) were observed only for the areas with Pearl millet and C1 and consortium 3 (C3), whereas the values were statistically similar for Brachiaria, Slenderleaf rattlebox, and C2. These variations in DM production occur naturally and are, in most cases, directly related to temperature and moisture conditions following planting. However, this factor did not appear decisive in this study, as the climatic conditions were consistent with those typically observed in the region (Figure 1).

The species used in this study under sole cropping (Brachiaria, Pearl millet, and Slenderleaf rattlebox) are known for producing dry matter (DM) of both high quantity and quality in the Brazilian Cerrado and are therefore the most widely used as soil cover in areas under no-till systems (NTS) (Assis et al., 2013; Pacheco et al., 2017a, b). The lower DM production observed for Brachiaria was due to its slow initial growth, as the plants had not yet reached full flowering at the time of management.

It has been proven that seed mixtures of Brachiaria, Pearl millet, and Slenderleaf rattlebox provide benefits to crops grown in succession (Torres et al., 2021, 2022; Silveira et al., 2021). Under natural conditions during the rainy season, these three species produced, respectively, 6 to 13 Mg ha^{-1}, 7 to 12 Mg ha^{-1}, and 4 to 9 Mg ha^{-1} of dry matter (Pacheco et al., 2013; Torres et al., 2014; Collier et al., 2018; Mazetto Júnior et al., 2019).

According to Silva et al. (2021), cover crop mixtures, especially those combining Poaceae and Fabaceae species, have been recommended to improve the soil physical, chemical, and biological quality. This practice offers several benefits, such as reducing N immobilization by soil microorganisms, increasing the availability of this nutrient in the soil, enhancing DM accumulation, improving water and nutrient use efficiency due to the exploration of different soil depths by contrasting root systems, and promoting greater soil decompaction, thereby improving its physical quality.

Crop mixtures in tropical conditions like Cerrado have ensured greater straw production and increased soil organic matter levels. According to Perin et al. (2010) and Teixeira et al. (2009), consortium with Pearl millet and Slenderleaf rattlebox can be an interesting alternative for no-till systems, as it provides biomass for soil cover and increases the nutrient content, particularly N and K.

Table 1. Dry matter (DM) production of different cover crops grown as sole crops and mixtures in areas under the transition and maintenance phases of the no-till system, in Uberaba, Minas Gerais, in 2024.

Cover crops	Dry matter (DM) production	
	Transition	Maintenance
	....Mg ha^{-1}..	
BR	9.33dA*	8.11 eA*
PM	10.99 cB	13.32 bA
SR	10.37 cA	9.56 dA
C1	13.70 bB	17.93 aA
C2	11.31 cA	10.67 cA
C3	15.38 aA	7.16 fB
F-test	55.11**	11.62**
CV%	6.94	9.27

Means followed by the same lowercase letters in the column compare cover crops, and uppercase letters in the lines compare periods, which do not differ according to the Scott–Knott test (** = p< 0.05). Consortium 1 (C1): *Brachiaria* (BR) *(Urochloa ruziziensis)*, Pearl millet (PM), Slenderleaf rattlebox (SR) (*Crotalaria ochroleuca*), Short-flowered rattlebox (*Crotalaria breviflora*), Buckwheat, Finger millet, and Crambe; Consortium 2: *Brachiaria*, Pearl millet, Finger millet, Forage sorghum, Cowpea, and Pigeon pea; Consortium 3: *Brachiaria ruziziensis*, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*C. breviflora*), Buckwheat, Finger millet, and Crambe; CV = Coefficient of variation.

Analyzing the decomposition rate of plant residues through regression analysis, it was observed that after 90 days, 51.7%, 58.3%, 49.6%, 54.0%, 54.1%, and 50.3% of DM remained for Brachiaria, Pearl millet, Slenderleaf rattlebox, and C1, C2 and C3, respectively, in the transition phase area, and 48.6%, 54.5%, 47.0%, 51.3%, 52.5%, and 48.5% of DM remained, respectively, in the maintenance phase area (Figure 2).

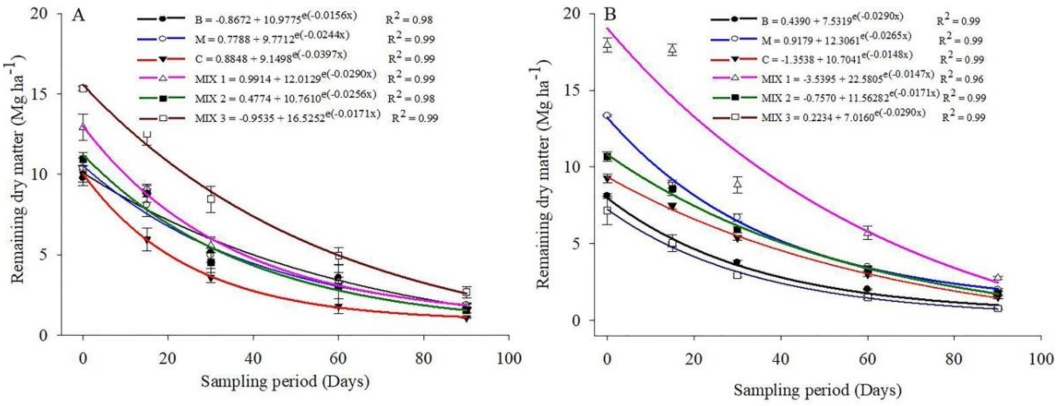

Figure 2. Remaining dry matter of residues from Brachiaria (B), Pearl millet (M), Slenderleaf rattlebox (C), and consortium 1, 2, and 3 at 0, 15, 30, 60, and 90 days after litterbag placement in the transition and maintenance phase areas of the no-till system, in Uberaba, MG.

The regression curves of residue decomposition show a more pronounced decline during the first 30 days after cover crop management (Figure 2), as also reported in studies conducted by Pacheco et al. (2011, 2013, 2017a), Collier et al. (2018), Torres et al. (2021), and Silveira et al. (2021), in which pearl millet exhibited the slowest decomposition and Slenderleaf rattlebox the fastest in the evaluated areas. This is likely because these species have the highest and lowest C/N ratios among the cover crops evaluated, whether grown alone or in mixtures.

At 15 days after placing the litterbags in the field, slenderleaf rattlebox showed the highest decomposition rate. This is due to the lower C/N ratio of Fabaceae species, resulting from their lower lignin content, as well as their ability to fix atmospheric N, which promotes faster residue decomposition compared to Poaceae species (Pacheco et al., 2013; Mazetto Junior et al., 2019; Torres et al., 2019, 2021, 2022).

Except for C3, after 30 days, all other cover crops, whether grown alone or in mixtures, showed no significant differences in the decomposition of the remaining biomass. This can be explained by the lack of soil moisture and the absence of significant rainfall in the region, due to a severe drought caused by the El Niño phenomenon. According to Torres and Pereira (2008), Torres et al. (2008), and Pacheco et al. (2017a, b), residue decomposition is directly influenced by soil temperature and moisture, as decomposition increases with higher values of these climatic variables during the rainy season and decreases to minimal levels during the dry season. This study observed this trend, as only 45.6 mm of rainfall was recorded during the evaluation period (Figure 1).

The decomposition constant (k) can estimate the half-life (T½) of the remaining dry matter on the soil surface. The results show that the values are close and vary across the evaluated periods; however, it is noteworthy that during the transition phase, Slenderleaf rattlebox residues had the shortest T½, while in the maintenance phase, the shortest T½ was observed for Brachiaria grown alone and for consortium 3, which included *C. ochroleuca* and *C. breviflora* in the seed mixture (Table 2).

In their studies, Assis et al. (2013), Mazetto Júnior et al. (2019), Silveira et al. (2021), and Torres et al. (2022) observed results similar to those obtained in this study when using Brachiaria as a cover crop. Brachiaria exhibited the highest residue decomposition rate compared to Slenderleaf rattlebox and Pearl millet, confirming that the lower C/N ratio observed in this species accelerated residue decomposition.

However, Marcelo et al. (2012) found that, in addition to the C/N ratio, analyzing lignin concentrations is important when characterizing plant materials left on the soil. Despite having a lower C/N ratio, Slenderleaf rattlebox residues showed low decomposition rates due to their higher lignin concentrations, which were observed in the area under the maintenance phase of the no-till system (NTS).

According to Giacomini et al. (2003), when mixing plants from families with inversely proportional C/N ratios, as with Fabaceae and Poaceae species, the resulting plant residues exhibit an intermediate C/N ratio. This leads to a lower decomposition rate of the mixed residues, ensuring longer-lasting soil cover, as confirmed in this study.

When evaluating the decomposition rate of plant residues from different cover crops, Torres et al. (2014) observed that this rate was faster initially and slowed down after 120 days. They attributed this to high precipitation during the initial phase and its scarcity in the final phase of the study. A similar pattern was observed in this study: while precipitation was high during the first 60 days (February and March 2024), residue decomposition was accelerated.

Table 2. Decomposition constant (k) and half-life (T½) of the remaining dry matter of different cover crops grown alone and in mixtures, in Uberaba, MG, in 2024.

Cover crops	Remaining dry matter			
	Total	K	T½ Life	R^2
	Mg ha^{-1}	g g^{-1}	days	--
		Transition		
BR	9.33 d	0.0156	44	0.98**
PM	10.99 c	0.0244	28	0.99
SR	10.37 c	0.0397	17	0.99
C1	13.70 b	0.0290	24	0.99
C2	11.31 c	0.0256	27	0.98
C3	15.38 a	0.0171	41	0.99
F-test	55.11**	--	--	--
CV (%)	6.94	--	--	--
		Maintenance		
	8.11 e	0.0290	24	0.99
PM	13.32 a	0.0265	26	0.99
SR	9.56 d	0.0148	47	0.99
C1	17.93 a	0.0147	47	0.96
C2	10.67 c	0.0171	41	0.99
C3	7.16 f	0.0290	24	0.99
F-test	11.62**	--	--	--
CV (%)	9.27	--	--	--

** = Significant ($p < 0.05$); R^2 = Coefficient of determination. Means followed by the same letter in the column do not differ according to the Scott–Knott test ($p < 0.05$). Consortium 1 (C1): Brachiaria (BR) (*Urochloa ruziziensis*), Pearl millet (PM), Slenderleaf rattlebox (SR) (*Crotalaria ochroleuca*), Short-flowered rattlebox (*Crotalaria breviflora*), Buckwheat, Finger millet, and Crambe; Consortium 2: Brachiaria, Pearl millet, Finger millet, Forage sorghum, Cowpea, and Pigeon pea; Consortium 3: *Brachiaria ruziziensis*, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*C. breviflora*), Buckwheat, Finger millet, and Crambe; CV = Coefficient of variation.

After precipitation decreased in April 2024 and ceased from May 2024 onward, decomposition slowed until the end of the study. Regarding nutrient accumulation in cover crop residues at the time of management in the transition phase area, it was observed that, overall, the highest accumulations of N (248.93 kg ha^{-1}), P (42.53 kg ha^{-1}), and Mg (25.13 kg ha^{-1}) occurred in C3; K (235.72 kg ha^{-1}) in C2; and Ca (51.024 kg ha^{-1}) and S (21.57 kg ha^{-1}) in C1. Conversely, the lowest accumulations of N (121.21 kg ha^{-1}), P (20.22 kg ha^{-1}), Ca (23.17 kg ha^{-1}), and Mg (15.90 kg ha^{-1}) were found in Brachiaria; K (197.21 kg ha^{-1}) in C3; and S (14.84 kg ha^{-1}) in Pearl millet (Table 3).

This greater accumulation of macronutrients in the residues is directly related to the higher dry matter production observed in consortium 1 (13.70 Mg ha^{-1}), 2 (11.31 Mg ha^{-1}), and 3 (15.38 Mg ha^{-1}), whereas the lower macronutrient accumulation in Brachiaria is due to its lower dry matter production (9.33 Mg ha^{-1}), which was lower than the values obtained for the other cover crops (Table 1).

Table 3. Macronutrient accumulation, decomposition constant (k), and half-life (T½) in the residues of cover crops used in a no-till system during the transition phase, in Uberaba, MG, 2024.

Cover crop	Macronutrients accumulated in waste						
	Nutrient	N	P	K	Ca	Mg	S
BR	Total (kg ha^{-1})	121.21 c	20.22 d	198.87 b	23.17 c	15.90 c	18.09 b
	k (g g^{-1})	0.0340	0.0312	0.0837	0.0183	0.0255	0.0308
	T½ (Days)	20	22	8	38	27	23
	R^2	0.97	0.99	0.99	0.99	0.99	0.99
PM	Total (kg ha^{-1})	164.08 b	22.48 d	199.04 b	25.40 c	19.42 b	14.84 b
	k (g g^{-1})	0.0292	0.1501	0.1920	0.0384	0.0998	0.1053
	T½ (Days)	24	5	4	18	7	7
	R^2	0.98	0.99	0.99	0.99	0.99	0.99
SR	Total (kg ha^{-1})	149.64 b	28.75 c	212.23 b	47.57 a	22.07 a	17.27 b
	k (g g^{-1})	0.0342	0.1224	0.1421	0.0289	0.0720	0.0520
	T½ (Days)	20	6	5	24	10	13
	R^2	0.99	0.99	0.99	0.99	0.98	0.99
C1	Total (kg ha^{-1})	191.14 b	33.63 b	210.76 b	51.24 a	22.19 a	21.57 a
	k (g g^{-1})	0.0324	0.0262	0.2634	0.0449	0.0395	0.0574
	T½ (Days)	21	26	3	15	18	12
	R^2	0.99	0.93	0.99	0.99	0.99	0.99

C2	Total (kg ha^{-1})	165.37 b	32.39 b	235.72 a	32.50 b	19.37 b	20.12 a
	k (g g^{-1})	0.0222	0.0673	0.1334	0.0245	0.0454	0.0902
	T½ (Days)	31	10	5	28	15	8
	R^2	0.99	0.99	0.99	0.98	0.99	0.92
C3	Total (kg ha^{-1})	248.93 a	42.53 a	197.21 b	48.07 a	25.13 a	20.12 a
	k (g g^{-1})	0.0406	0.1306	0.1170	0.0461	0.0323	0.1033
	T½ (Days)	17	5	6	15	21	7
	R^2	0.96	0.99	0.99	0.99	0.99	0.98
F-test		13.94**	57.29**	6.74**	24.34**	8.20**	5.49**
CV (%)		25.83	13.73	22.24	27.13	14.71	19.38

= Significant ($p < 0.05$). Means followed by the same letter in the column compare the cover crops and do not differ from each other according to the Scott–Knott test ($p < 0.05$). R² = Coefficient of determination; Consortium 1 (C1): *Brachiaria* (BR) *(Urochloa ruziziensis)*, Pearl millet (PM), Slenderleaf rattlebox (SR) (*Crotalaria ochroleuca*), Short-flowered rattlebox (*Crotalaria breviflora*), Buckwheat, Finger millet, and Crambe; Consortium 2: *Brachiaria*, Pearl millet, Finger millet, Forage sorghum, Cowpea, and Pigeon pea; Consortium 3: *Brachiaria ruziziensis*, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*C. breviflora*), Buckwheat, Finger millet, and Crambe; CV = Coefficient of variation.

N and K are the nutrients most demanded by most plant species, with requirements up to five times higher than P and accumulating two to three times more than Ca, whereas S is the least required and therefore the least accumulated (Brady and Weil, 2013). This study observed this pattern, with an N/P ratio of approximately 5.8. In the maintenance phase area, the highest macronutrient accumulation was observed in C1 for N (272.70 kg ha^{-1}), P (53.02 kg ha^{-1}), K (212.54 kg ha^{-1}), Mg (38.35 kg ha^{-1}), and S (36.59 kg ha^{-1}), and in Pearl millet for Ca (56.35 kg ha^{-1}). The lowest values were found in C3 for N (101.83 kg ha^{-1}), P (13.41 kg ha^{-1}), Ca (24.10 kg ha^{-1}), and S (14.52 kg ha^{-1}), and in Brachiaria for K (100.42 kg ha^{-1}) and Mg (15.96 kg ha^{-1}). The other plants, whether grown alone or in mixtures, presented intermediate values (Table 4).

Table 4. Macronutrient accumulation, decomposition constant (k), and half-life (T½) in the residues of cover crops used in the maintenance phase area under the no-till system, in Uberaba, MG, in 2024.

Cover crop	Macronutrients accumulated in waste						
	Nutrient	N	P	K	Ca	Mg	S
BR	Total (kg ha^{-1})	129.65 d	18.64 d	100.42 c	25.50 c	15.96 d	14.83 d
	k (g g^{-1})	0.0383	0.1145	0.1135	0.0303	0.0465	0.0863
	T½ (Days)	18	6	6	23	15	8
	R^2	0.98	0.98	0.99	0.95	0.98	0.99
PM	Total (kg ha^{-1})	192.38 b	30.15 b	206.96 a	56.35 a	29.43 b	22.37 b
	k (g g^{-1})	0.0382	0.1093	0.1608	0.0758	0.1593	0.0670
	T½ (Days)	18	6	4	9	4	10
	R^2	0.99	0.99	0.99	0.99	0.99	0.99
SR	Total (kg ha^{-1})	157.41 c	28.74 b	132.13 b	24.43 c	21.21 c	14.42 d
	k (g g^{-1})	0.0382	0.1069	0.1837	0.0187	0.0506	0.0932
	T½ (Days)	18	6	4	37	14	7
	R^2	0.98	0.99	0.99	0.98	0.98	0.99
C1	Total (kg ha^{-1})	272.70 a	53.02 a	212.54 a	53.95 a	38.35 a	36.59 a
	k (g g^{-1})	0.0257	0.0699	0.1435	0.0180	0.0463	0.0822
	T½ (Days)	3	10	5	39	15	8
	R^2	0.99	0.99	0.99	0.99	0.99	0.99
C2	Total (kg ha^{-1})	134.71 d	25.26 c	133.24 b	35.46 b	21.61 c	18.33 c
	k (g g^{-1})	0.0151	0.0636	0.1220	0.0270	0.0345	0.0598
	T½ (Days)	46	11	6	26	20	12
	R^2	0.99	0.99	0.99	0.98	0.99	0.92
C3	Total (kg ha^{-1})	101.83 c	13.41 e	120.76 b	24.10 c	16.51 d	14.52e
	k (g g^{-1})	0.0402	0.0700	0.2003	0.0329	0.0872	0.1093
	T½ (Days)	17	10	3	21	8	6
	R^2	0.99	0.99	0.99	0.98	0.99	0.98
F-test		136.10**	68.96**	43.60**	52.82**	66.80**	56.14**
CV (%)		13.08	22.23	19.93	17.77	17.21	20.40

= Significant ($p < 0.05$). Means followed by the same letter in the column compare the cover crops and do not differ from each other according to the Scott–Knott test ($p < 0.05$). R² = Coefficient of determination; Consortium 1 (C1): *Brachiaria (BR) (Urochloa ruziziensis)*, Pearl millet (PM), Slenderleaf rattlebox (SR) (*Crotalaria ochroleuca*), Short-flowered rattlebox (*Crotalaria breviflora*), Buckwheat, Finger millet, and Crambe; Consortium 2: *Brachiaria*, Pearl millet, Finger millet, Forage sorghum, Cowpea, and Pigeon pea; Consortium 3: *Brachiaria ruziziensis*, Slenderleaf rattlebox (*C. ochroleuca*), Short-flowered rattlebox (*C. breviflora*), Buckwheat, Finger millet, and Crambe; CV = Coefficient of variation.

Regarding T½, the lowest values were observed for K, confirming its high mobility in the soil and plant, as rainwater easily leaches it. According to Meurer (2004), the high mobility of K is since this element is not part of any structure or organic molecule, being found adsorbed or as a free cation.

Overall, macronutrient accumulation in the maintenance phase area was lower for most of the cover crops than those grown during the same period in the transition phase area, except for consortium 1. This consortium had the highest dry matter production (17.93 Mg ha^{-1}), which was 31% higher compared to the production obtained during the transition phase (13.70 Mg ha^{-1}) (Table 1). Nutrient accumulation varied according to the cover crops grown alone or in mixtures. In general, the order of the accumulated nutrient amounts absorbed by the plants was as follows: K > N > Ca > P > Mg > S.

In Uberaba, Minas Gerais, under natural conditions, Torres et al. (2008) and Torres and Pereira (2008) quantified the dry matter production of Brachiaria, Pearl millet, and Slenderleaf rattlebox, which were 6.0, 10.3, and 3.9 t ha^{-1}, respectively. These values corresponded to nutrient accumulations of N (130.80, 165.55, and 118.11 kg ha^{-1}), P (13.30, 22.60, and 10.80 kg ha^{-1}), K (214.70, 218.90, and 59.20 kg ha^{-1}), Ca (18.70, 41.12, and 42.60 kg ha^{-1}), Mg (21.10, 22.60, and 12.80 kg ha^{-1}), and S (9.00, 13.40, and 4.20 kg ha^{-1}) during the rainy season. These values are lower than those obtained in this study for the same area and time of year, across both evaluated phases (transition and maintenance). In the dry season, the dry matter production for these same crops was 2.1, 3.6, and 3.7 Mg ha^{-1}, with nutrient accumulations of N (41.65, 55.75, and 76.38 kg ha^{-1}), P (2.33, 4.71, and 4.06 kg ha^{-1}), K (45.79, 56.47, and 39.11 kg ha^{-1}), Ca (8.69, 23.17, and 22.14 kg ha^{-1}), Mg (5.94, 11.22, and 6.64 kg ha^{-1}), and S (3.18, 6.52, and 4.06 kg ha^{-1}), which were lower ($p < 0.05$) compared to the rainy season.

In Selvíria, Mato Grosso do Sul, Leal et al. (2013) evaluated the DM of pearl millet and Slenderleaf rattlebox and observed productions of 4.2 and 4.2 t ha^{-1}, respectively, with nutrient accumulations of N (50.5 and 107.3 kg ha^{-1}), P (9.6 and 12.1 kg ha^{-1}), K (49.2 and 72.5 kg ha^{-1}), Ca (22.5 and 45.2 kg ha^{-1}), and Mg (15.0 and 16.8 kg ha^{-1}) in their residues.

Meanwhile, Silva et al. (2017), in the same region, observed Slenderleaf rattlebox DM production of 19.7 and 11.4 t ha^{-1} in 2015 and 2016, respectively, with nutrient accumulations of N (387.5 and 394.2 kg ha^{-1}), P (66.3 and 45.9 kg ha^{-1}), K (396.0 and 192.7 kg ha^{-1}), Ca (134.7 and 69.1 kg ha^{-1}), Mg (69.0 and 51.1 kg ha^{-1}), and S (55.8 and 77.9 kg ha^{-1}). These results demonstrate that the amount of dry matter produced by the cover crops directly influences the amount of accumulated nutrients, which was also observed in this study.

In Rio Verde, Goiás, under natural conditions, Pacheco et al. (2011) quantified the DM of Brachiaria and Pearl millet at 6.2 and 2.4 Mg ha^{-1}, respectively, in the 2008/09 crop season, with high nutrient accumulations of N (116.1 and 29.3 kg ha^{-1}), P (10.4 and 2.6 kg ha^{-1}), K (92.9 and 12.7 kg ha^{-1}), Ca (53.8 and 8.9 kg ha^{-1}), and Mg (11.6 and 3.8 kg ha^{-1}). In the following crop season (2009/10), DM production increased to 7.5 and 6.1 t ha^{-1}, with higher nutrient accumulations of N (98 and 78.8 kg ha^{-1}), P (19.6 and 16.2 kg ha^{-1}), K (112.4 and 53.8 kg ha^{-1}), and Ca (63.7 and 49.0 kg ha^{-1}), compared to the previous year values that are still lower than those found in this study.

Through the regression curves of nutrient release, it was observed during the transition phase that K was released more rapidly across all evaluated cover crops, and a similar pattern was seen for P in Pearl millet, Slenderleaf rattlebox, and consortium 2 and 3 (Figure 3), which exhibited a T½ ranging from 3 to 10 days (Table 3). This indicates that half of the nutrients retained in the leaf tissues were cycled back to the soil within this period (Table 3).

N is one of the most abundant and required elements for various plant species; however, in this study, its release was slow across all treatments. This is uncommon, as N is typically a highly mobile element in the soil (Meurer, 2004) and is also subject to leaching by rainfall (Torres et al., 2021). The treatment with only Brachiaria showed the slowest and most consistent N release into the soil. Carvalho et al. (2021) observed that Poaceae species take longer to release N, and in smaller quantities, a pattern also observed in this study.

When evaluating the production, decomposition, and nutrient cycling of residues from Slenderleaf rattlebox and Pearl millet, grown either as sole crops or in mixtures, Soratto et al. (2012) observed that Pearl millet produces a greater amount of dry matter and accumulates more N, P, K, Mg, S, C, and Si, whereas Slenderleaf rattlebox accumulates more Ca. They also noted that Pearl millet dry matter exhibits a higher decomposition rate and nutrient release. The authors concluded that the highest decomposition rates and daily nutrient release from residues occur between the 1st and 18th day after management. They further observed that, over time, the C/N, C/P, and C/S ratios increase, while the C/Si ratio and the decomposition rate of dry matter decrease. Additionally, they reported that K is the nutrient most rapidly made available to the soil, whereas Si has the lowest release rate.

Regarding P accumulation and release, except for consortium 2 and Brachiaria, the treatments showed a rapid initial release of this macronutrient, which stabilized after 20 days following residue cutting, with a slower release thereafter. In Cerrado soils, P availability is low, reducing its accumulation in plant biomass.

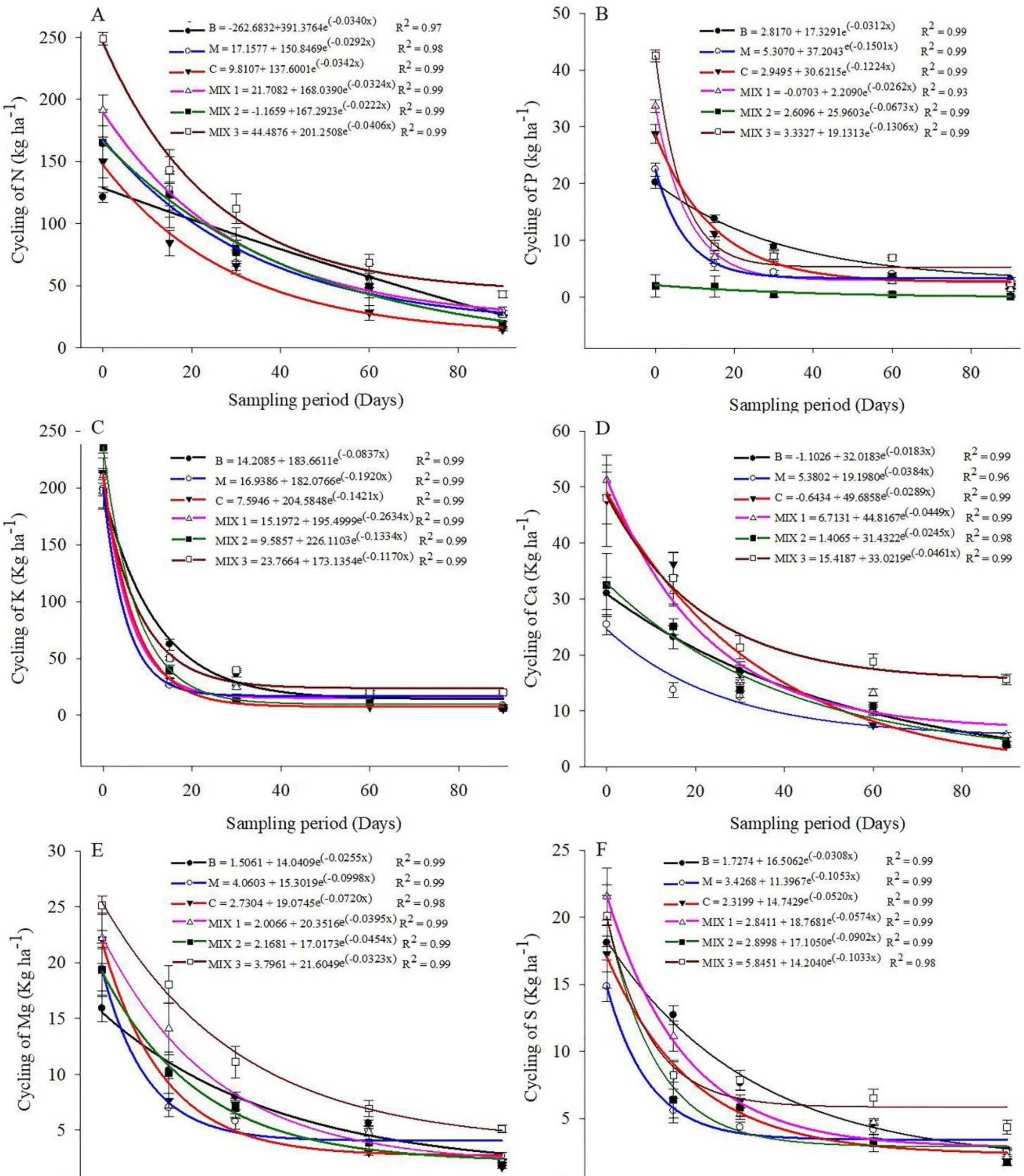

Figure 3. Cycling of N (A), P (B), K (C), Ca (D), Mg (E), and S (F) from the residues of Brachiaria (B), Pearl millet (M), Slenderleaf rattlebox (C), and Consortium 1, 2, and 3 at 0, 15, 30, 60, and 90 days after litterbag placement, in the transition phase area of the no-till system, in Uberaba, MG, in 2024.

K was released rapidly in all treatments, which is explained by the fact that this element is not bound to any structural components of plant tissues, thus increasing its availability in the soil (Ferreira et al., 2014). N, one of the most abundant and highly required elements by various plant species, was released slowly across all treatments. The treatment with sole-cropped Brachiaria released N into the soil most slowly and consistently. Carvalho et al. (2021) observed that grass species take longer to release N, and in smaller quantities, a pattern also observed in this experiment.

The consortium of Fabaceae and Poaceae species with other plants allows for combining the individual benefits of each species, mitigating the issue of low individual dry matter production while providing more persistent residue cover. It also helps alleviate N deficiency during the early stages of the succeeding crop and recycles nutrients with high mobility in the soil (Calvo et al., 2010).

Regarding P accumulation and release, except for consortium 2 and Brachiaria, the treatments showed a rapid initial release of this macronutrient, which stabilized after 20 days following residue cutting, with a slower release thereafter. Due to the low P availability in Cerrado soils, combined with the high export of this nutrient to grains, it is likely that the species, at the onset of flowering, translocated a significant portion of P to other parts of the plants, reducing its availability.

In Figure 4, the regression curves exhibit a decreasing exponential function, with consortium 1 being the treatment that achieved the highest nutrient accumulation during the maintenance phase and the greatest nutrient release. All macronutrients had a T½ ranging from 3 to 15 days, except for Ca, which had a T½ of 39 days and was released more slowly (Table 4).

Favarato et al. (2020) also observed a gradual release of Ca from Poaceae residues, with a T½ of 41 days. Because it is part of the structural composition of cells and serves as a cofactor for some enzymes in the hydrolysis of adenosine triphosphate (ATP) and phospholipids, this nutrient has greater difficulty being mineralized in the biomass and released into the soil (Taiz and Zeiger, 2024).

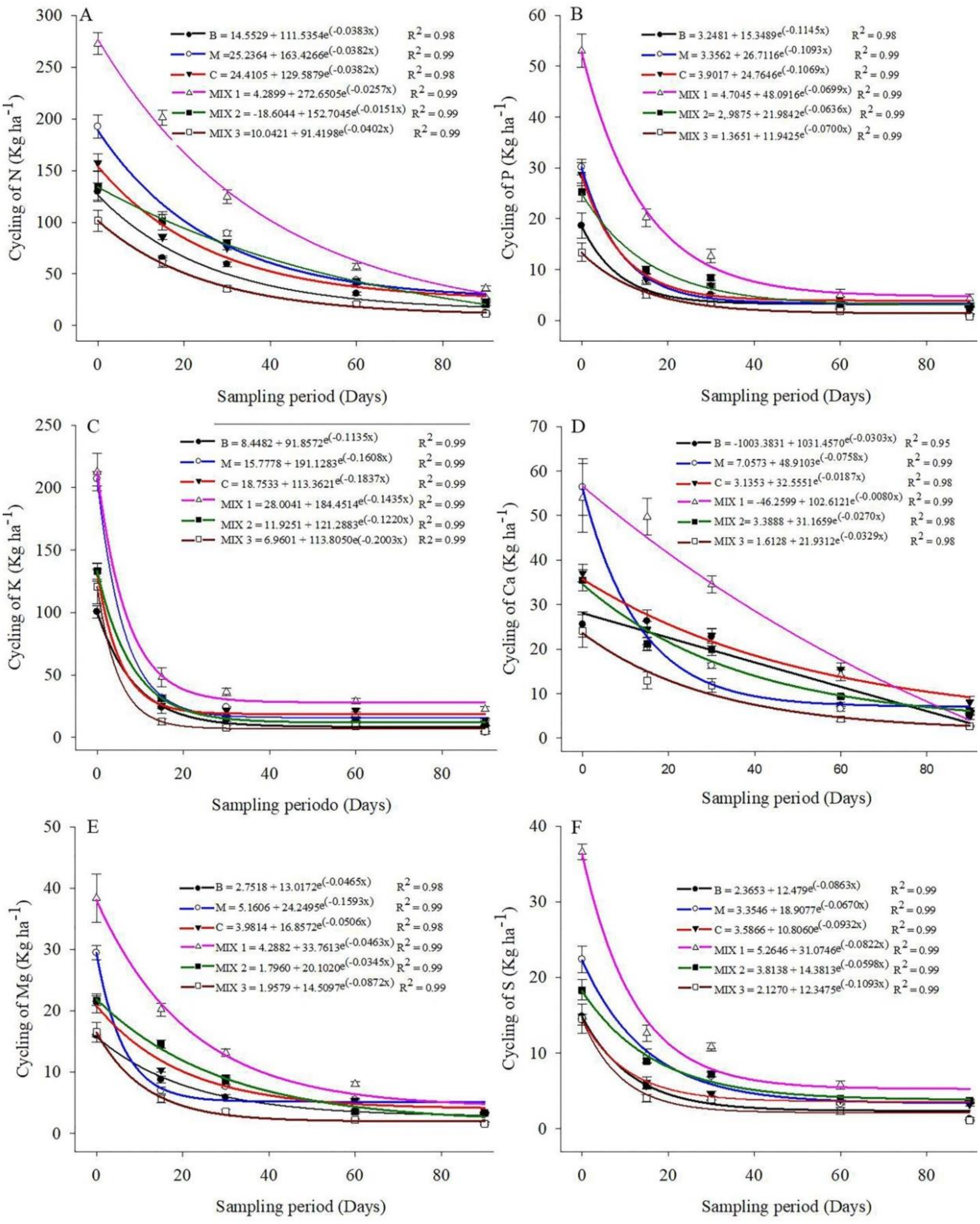

Figure 4. Cycling of N (A), P (B), K (C), Ca (D), Mg (E), and S (F) from the residues of Brachiaria (B), Pearl millet (M), Slenderleaf rattlebox (C), and Consortium 1, 2, and 3 at 0, 15, 30, 60, and 90 days after litterbag placement, in the maintenance phase area of the no-till system, in Uberaba, MG, in 2024.

As observed during the transition phase, a rapid release of K into the soil was also noted for all treatments during the maintenance phase of the no-till system (NTS). By 20 days, more than 50% of the residue K content had already been released. Because it forms bonds with organic complexes that are easily reversible, as the cover crop biomass decomposes, the K in the residues is easily leached by rainwater and released into the soil (Torres and Pereira, 2008; Mateus et al., 2017; Favarato et al., 2020).

P was also rapidly released into the soil, as the T½ ranged from 6 to 11 days for all evaluated cover crops. In other words, 50% of the P retained in the cover crop residues was made available in the soil to be absorbed by the succeeding crops. The regression curves of nutrient release during the transition (Figure 3) and maintenance (Figure 4) phases showed that K, P, and S were the most rapidly cycled back into the soil across all evaluated cover crops, compared to N, Ca, and Mg. These results differ from those reported in some studies, which indicate that the most rapidly cycled nutrients are K, N, and Ca (Soratto et al., 2012; Pacheco et al., 2013; 2017a; Torres et al., 2021, 2022).

4. Conclusions

The highest dry matter production among the cover crops occurred in consortium 3 (15.38 Mg ha^{-1}) during the transition phase and consortium 1 (17.93 Mg ha^{-1}) during the maintenance phase. Dry matter production was higher for all cover crops during maintenance except consortium 3.

The highest decomposition rate and residue T½ occurred in Slenderleaf rattlebox (49.6% and 17 days) during the transition phase, and in Brachiaria (48.6% and 24 days) and consortium 3 (48.5% and 24 days), which were equal during the maintenance phase, respectively.

In the transition phase, the highest nutrient accumulation occurred in consortium 3 for N (248.93 kg ha^{-1}), P (42.53 kg ha^{-1}), and Mg (25.13 kg ha^{-1}); in consortium 2 for K (235.72 kg ha^{-1}); and in consortium 1 for Ca (51.024 kg ha^{-1}) and S (21.57 kg ha^{-1}). In the maintenance phase, the highest accumulation of N (272.70 kg ha^{-1}), P (53.02 kg ha^{-1}), K (212.54 kg ha^{-1}), Mg (38.35 kg ha^{-1}), and S (36.59 kg ha^{-1}) was found in consortium 1, while Ca accumulation (56.35 kg ha^{-1}) was observed in Pearl millet.

The accumulated K, P, and S levels in the plant residues were cycled back into the soil more rapidly across all cover crops during the transition and maintenance phases. Residue decomposition and nutrient cycling are higher during the maintenance phase than during the transition phase.

Authors' Contribution

Robson Martins de Oliveira and José Luiz Rodrigues Torres designed the project, submitted it as a dissertation project, participated in all its stages, and drafted the initial version of the manuscript. Rafael Daineis and Dinamar Márcia da Silva Vieira assisted with all sample collections and their processing in the soil physics laboratory. Valdeci Orioli Júnior and Daniel Pena Pereira reviewed and revised the entire manuscript text. José Luiz Rodrigues Torres and Valdeci Orioli Júnior were responsible for the statistical analysis, assisted with data tabulation and interpretation, and handled the formatting of the manuscript according to the journal guidelines.

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