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RESEARCH

Cover crop dynamics in organic systems in Southeastern Brazil: the role of season and soil management

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Abstract This study evaluated the effects of seasonality, soil management (no-till and conventional tillage), and different cover crop combinations on (i) aboveground dry biomass production, nutrient content, and accumulation; (ii) residue decomposition; and (iii) nutrient release (N, P, K). The experiment was conducted in summer and winter at the certified organic farm Sítio do Sol, Seropédica, Rio de Janeiro, Brazil. A randomized complete block design with three replicates was used in a 2×6 split-plot scheme. Main plots were two soil management systems: no-till (NT) and conventional tillage (CT). Subplots included six cover crop treatments: millet (M) (*Pennisetum glaucum*), sunn hemp (CJ) (*Crotalaria juncea*), jack bean (JB) (*Canavalia ensiformis*), two mixtures of these three cover crops (C1 = 100% seeding rate; C2 = 50% for each cover crop), and spontaneous vegetation (SP). Aboveground dry biomass production and nutrient accumulation were higher in summer, especially for CJ, C1, and C2, with CJ reaching 10.32 Mg ha^{-1} and 250.32 kg N ha^{-1}. Winter crops had higher nutrient concentrations (g kg^{-1}), contributing to a lower C/N ratio and slower decomposition. Decomposition was faster in summer, with the quickest breakdown in C1 (k = 0.0193 g g^{-1}; $T_1/_2$ = 36 days). Nutrient release patterns were generally consistent across seasons, with K having the shortest half-life (16 days in summer; 15 in winter). CJ is recommended for summer due to its aboveground dry biomass and nutrient contributions, while

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C1 and C2 mixtures are more effective in winter. The results highlight the seasonal variability in cover crop performance and the need for species-specific strategies in organic no-till systems.

Keywords Management · Mulch · Nutrient cycling · Seasonality

Introduction

Agricultural land plays a vital role in ensuring global food security, yet the sustainability of food production systems depends largely on the conservation and resilience of natural ecosystems. Among these, the soil ecosystem is central to crop productivity, acting as a reservoir of water, biodiversity, and essential nutrients. However, nutrient limitations in agricultural soils are common, often requiring the application of fertilizers to meet crop demands. In Brazil, fertilizer imports have shown a continuous upward trend, with an 11.2% increase recorded in January 2025 compared to January 2024 (Conab 2025). Over the past five years, the volume of imported fertilizers has steadily risen: 41.47 million tons were imported in 2021, 38.12 million tons in 2022, 40.91 million tons in 2023, 44.28 million tons in 2024, and 45.50 million tons in 2025. The states of Mato Grosso, Paraná, and São Paulo stand out as the largest consumers in the country, underscoring Brazil's growing reliance on external agricultural inputs (Conab 2026).

To reduce dependency on imported fertilizers and associated costs, one sustainable alternative is the use of cover crops. These crops not only improve soil fertility and nutrient cycling but also contribute to the protection of soil and water resources. Hudek et al. (2022) evaluated different root systems of cover crops and observed that root system characteristics were positively correlated with soil physical properties, particularly with reduced compaction and improved soil aggregation. The authors highlight that the strategic use of cover crops with well-developed root systems can be an effective tool for farmers in soil conservation and the improvement of soil structural quality. As a result, farmers may reduce their dependence on synthetic fertilizers and other external inputs. This reduced reliance on synthetic inputs also supports food security by enhancing the stability of agricultural production and access to nutritious food (Zhang et al. 2022; Liu et al. 2022; Fao 2025).

The adoption of such agroecological practices aligns with the United Nations' Sustainable Development Goals (SDGs), especially Goal 2 (Zero Hunger and Sustainable Agriculture), Goal 3 (Good Health and Well-being), Goal 13 (Climate Action), and Goal 15 (Life on Land) (UN 2025). Within this context, integrating cover crops into conservation agriculture systems particularly no-till farming (NT) is fundamental. No-till systems are guided by three core principles: crop rotation, minimal soil disturbance, and continuous soil cover (Bertol et al. 2016; Pires et al. 2020).

In no-till systems, cover crops contribute organic residues that differ in chemical composition depending on species. Grasses, characterized by high carbon-to-nitrogen (C/N) ratios, decompose more slowly and are effective for maintaining soil cover. In contrast, legumes with lower C/N ratios decompose more rapidly and enhance nutrient availability through biological nitrogen fixation (Hunter et al. 2019). When grown in mixtures, these species offer a balance between prolonged soil coverage and efficient nutrient cycling, making them especially suitable for organic systems where synthetic inputs are prohibited (Koudahe et al. 2022).

Cover crops such as jack bean (*Canavalia ensiformis*), sunn hemp (*Crotalaria juncea*), and millet (*Pennisetum glaucum*) are widely used in tropical regions, either as monocultures or intercropped. Under favorable spring–summer conditions, these species can produce substantial aboveground dry biomass, ranging from 5–15 Mg ha^{-1} (Carvalho et al. 2022). However, cover crop performance is highly influenced by seasonal climatic variations. Summer typically brings higher temperatures and rainfall, promoting faster growth, whereas winter conditions may limit development and biomass accumulation. This seasonality also affects decomposition rates and nutrient release dynamics, which are critical to optimizing the ecological functions of cover crops in organic systems (Jatobá and Silva 2020).

The persistence of crop residues on the soil surface is another key aspect influenced by environmental factors. Warm and humid climates accelerate decomposition, potentially reducing mulch longevity and its protective functions. Therefore, selecting cover crops that can produce sufficient biomass and decompose at

rates compatible with soil cover goals is essential for the successful implementation of no-till systems in tropical regions (Alvarenga et al. 2001; Araújo et al. 2015).

In light of these considerations, this study aimed to evaluate the effects of seasonality, soil management systems (conventional tillage and no-till), and different combinations and species of cover crops within an organic agriculture context on: (i) aboveground dry biomass production, nutrient content, and nutrient accumulation; (ii) the decomposition dynamics of cover crop residues; and (iii) the release patterns of nitrogen, phosphorus, and potassium. The findings aim to support strategic cover crop selection and management to enhance nutrient cycling and maintain effective soil cover throughout seasonal transitions in tropical organic farming systems.

Materials and methods

Site description and experimental design

The experiment was conducted at *Sítio do Sol*, a certified organic farm located in Seropédica, Rio de Janeiro, Brazil (22°49′20.3″ S, 43°44′19.4″ W, 26 m altitude). The region has a tropical savanna climate (Aw, according to Köppen and Geiger 1928), characterized by a rainy summer and a dry winter. The annual rainfall averages approximately 1,244.8 mm (Inmet 2025). The summer season extended from December 21, 2022, to March 20, 2023 (Fig. 1 a), and winter from June 20 to September 22, 2023 (Fig. 1b). Higher rainfall and temperatures were recorded during the summer (Fig. 1a).

Sítio do Sol is a member of ABIO (Association of Organic Farmers of the State of Rio de Janeiro) and is listed in the National Register of Organic Producers (CNPO). The farm holds an organic certification seal under the Brazilian Organic Conformity Assessment System (SisOrg) and is regularly inspected by a Participatory Organic Conformity Assessment Body (OPAC).

The soil at the experimental site is classified as Yellow Argisol with a sandy texture in the 0–20 cm layer (Santos et al. 2018). The field was established in 2018, initially by removing pasture and planting black oat (*Avena strigosa*) to homogenize the area. In 2019, two contrasting soil management systems were implemented after cutting the oats: (1) no-till (NT), the cover crops were mechanically cut using a brush cutter, with the roots left intact in the soil, and the plant residues were left on the soil surface, and (2) conventional tillage (CT), where residues were incorporated and soil was plowed. Green corn (*Zea mays*) was subsequently sown in both systems, and a crop rotation was maintained, including cover crops and economically relevant species. During the 2022/2023, when evaluations were conducted on summer and winter cover crops, the rotational crops were popcorn maize (*Zea mays everta*) and green bean (*Phaseolus vulgaris* L.) (Fig. 2).

The experimental layout followed a randomized block design in a 2×6 split-plot arrangement with three replicates. Main plots represented two soil management systems (NT and CT), and subplots contained six cover crop treatments: three monocultures millet (*Pennisetum glaucum*, M), sunn hemp (*Crotalaria juncea*, CJ), and jack bean (*Canavalia ensiformis*, JB); two mixtures C1 (100% of the recommended seeding rate for each species) and C2 (50% rate); and spontaneous plants (SP) during fallow. The seeding density of the cover crops was 60 kg ha^{-1} for M, 40 kg ha^{-1} for CJ, and 200 kg ha^{-1} for JB, corresponding to 100% of the recommended seeding rate for each species. In the C2 treatment, 50% of this density was used for each cover crop, according to Carvalho et al. (2022) (Fig. 3).

Each main plot measured 144 m^2 (24×6 m), and subplots were 24 m^2 (6×4 m). In CT plots, soil preparation was done using a Brazilian-made Yanmar TC14 Super walk-behind tractor with rotary blades. In NT plots, cover crops were mowed and left on the surface to simulate natural mulching. Cover crop treatments and subsequent analyses were performed during both summer and winter seasons.

Sampling and laboratory analysis

When cover crops reached 50% flowering, plants were harvested for biomass quantification using a 1.5×1.5 m PVC square (2.25 m^2), randomly placed within each subplot. All aboveground biomass was cut at the soil surface, collected within the sampling frame, and immediately weighed to determine fresh biomass (i.e., plant mass including water content). For mixed treatments, individual species (millet, sunn hemp, and jack bean) were separated and weighed

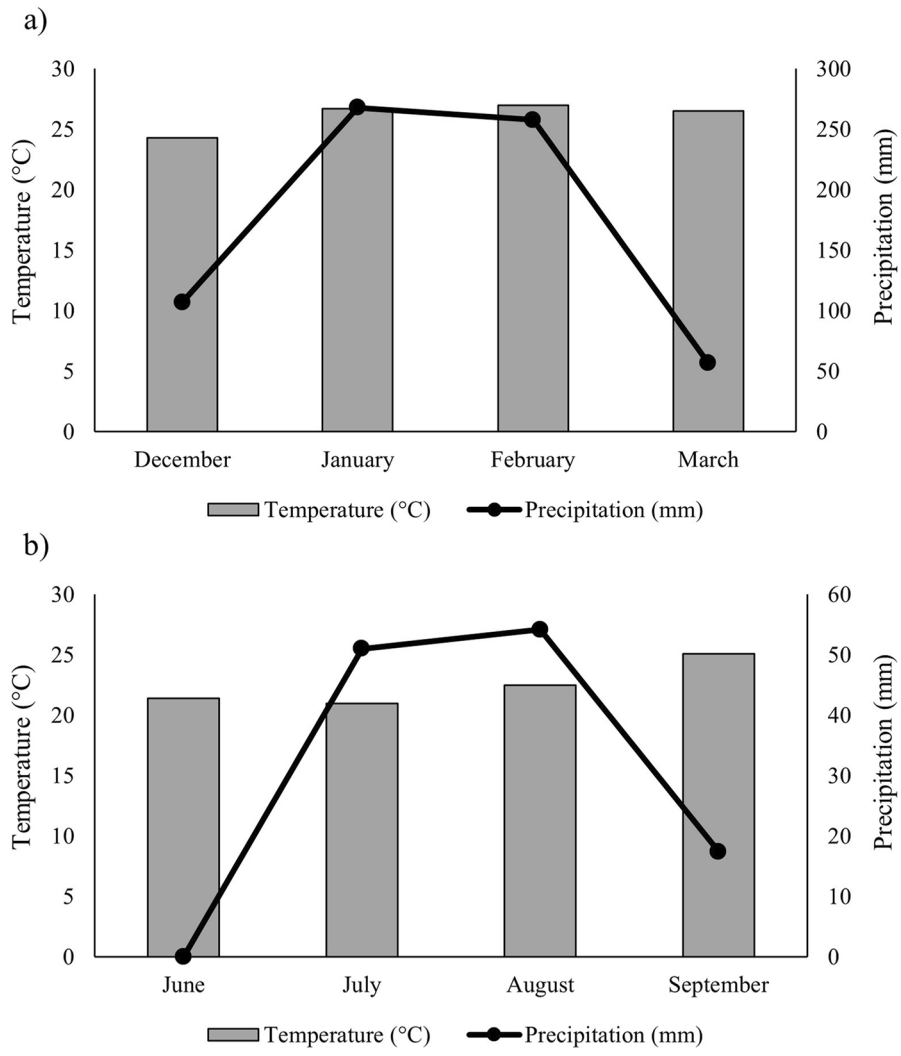


Fig. 1 Rainfall and temperature during the summer (**a**) and winter (**b**) seasons of 2022/2023

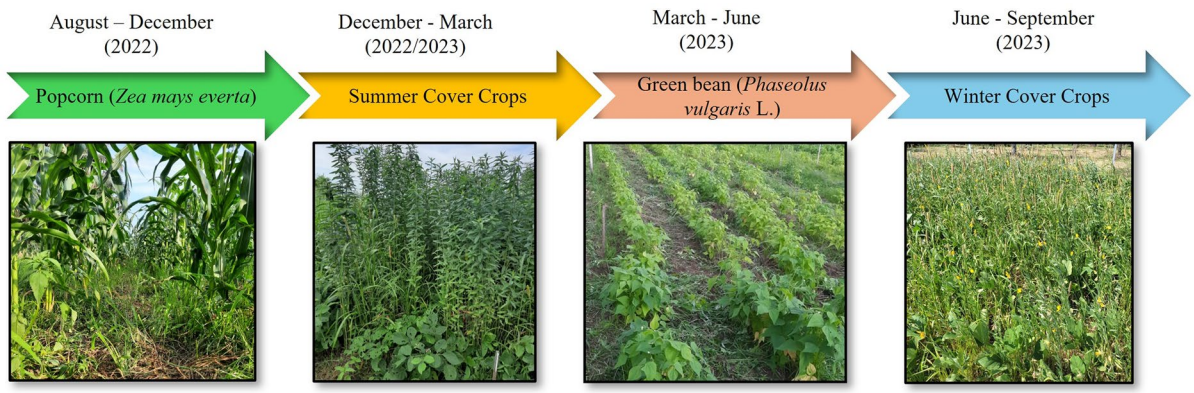


Fig. 2 Rotation of cover crops with cash crops during the 2022/2023 growing season

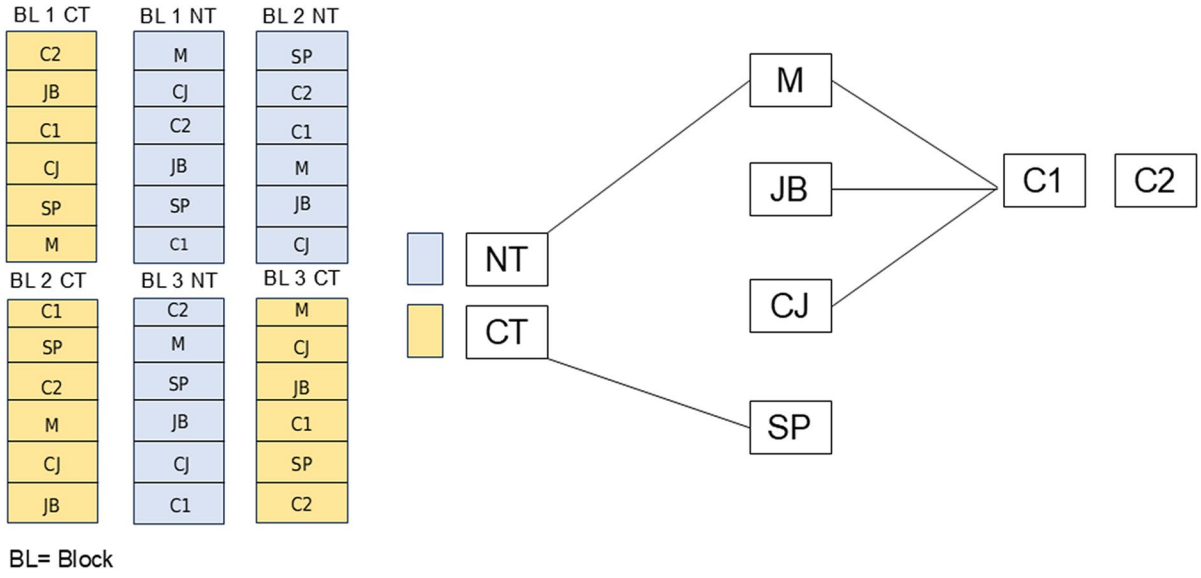


Fig. 3 Layout of experimental plots (soil management) and subplots (cover crops)

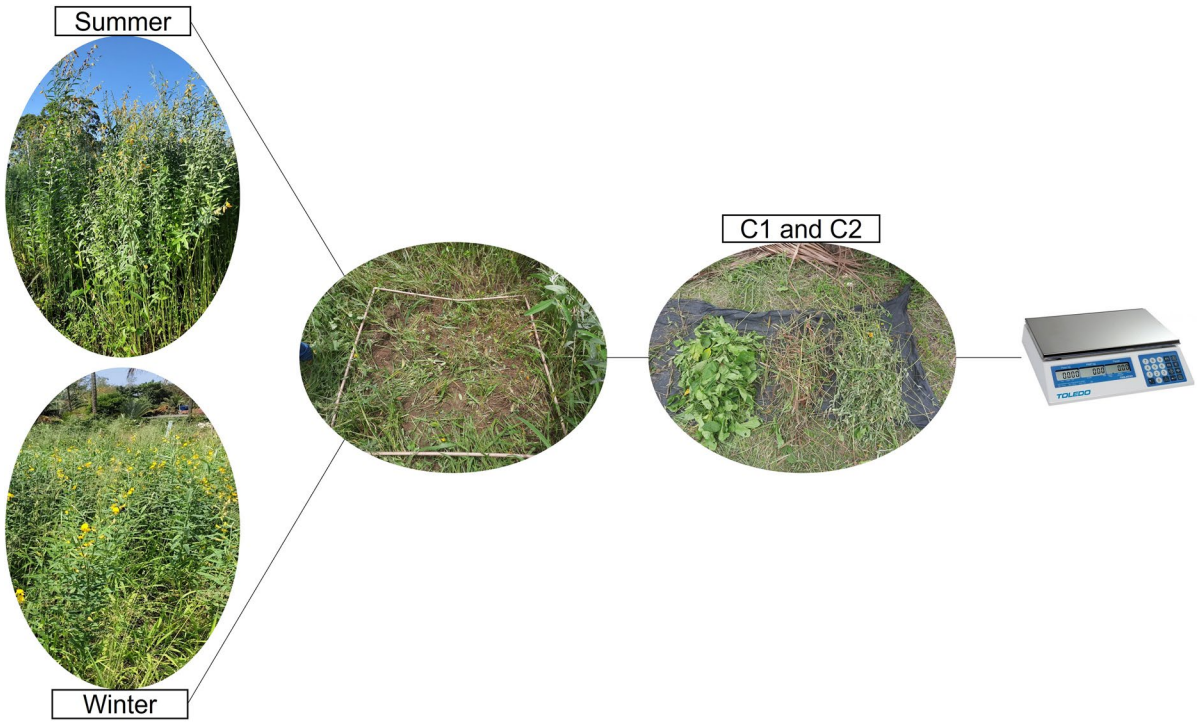


Fig. 4 Collection, separation, and weighing cover crops during summer and winter

independently (Fig. 4). Subsequently, the samples were oven-dried at 65 °C for 72 h until constant weight to determine aboveground dry biomass, which was expressed in Mg ha^{-1}.

Dried samples were ground using a Wiley mill with a 2 mm mesh. Samples were digested in sulfuric acid for nutrient analysis. Nitrogen (N) was determined using the Kjeldahl method, phosphorus (P) by colorimetry, and potassium (K) by flame photometry, according to Tedesco et al. (1995). Nutrient accumulation (kg ha^{-1}) was calculated by multiplying nutrient concentration (g kg^{-1}) by aboveground dry biomass (Mg ha^{-1}).

To evaluate decomposition and nutrient release, litterbags (20×20 cm, 2 mm mesh) were filled with 10 g of dried plant material and placed on the soil surface in NT plots to simulate mulching. Four bags per subplot were retrieved at 15, 30, 60, and 90 days post-deposition. After collection, samples were oven-dried at 65 °C to constant weight and reweighed to assess mass loss. Ground samples were analyzed for N, P, and K content following the same methods.

Decomposition rates and nutrient release were modeled using the negative exponential decay equation (Thomas and Asakawa 1993):

$$X = Xo.e^{-k.t}$$

where X is the remaining dry matter at time t, X_o is the initial mass, and k is the decomposition constant. The equation was linearized as:

$$k = \ln(X/Xo)/t$$

The half-life ($T^{1/2}$) of dry matter or nutrients was calculated as (Paul and Clark 1996):

$$T^{1/2} = \ln(2)/\ k$$

representing the time required for 50% decomposition or nutrient release (Espíndola et al. 2006). SigmaPlot v10.0 was used to fit mathematical models for decomposition and nutrient release curves.

Statistical analysis

Experimental units presented low within-plot variability and no relevant spatial autocorrelation. The low within-plot variability was confirmed by variance component analysis and by inspection of residuals from preliminary models, which indicated homogeneous residual variance among experimental units within plots. Therefore, a linear mixed-effects model (R packages *lme4* v1.1.23 and *lmerTest* v3.1–2) was used to assess the influence of soil management, cover crop treatment, and season on aboveground dry biomass, nutrient content, nutrient accumulation, and C/N ratio. Soil management, cover crop type, and season were treated as fixed effects, and blocks were treated as a random effect.

Type II Wald χ^2 tests and least squares means were used for post hoc comparisons with false discovery rate correction (*R* packages lmerTest v3.1–2 and lsmeans v2.30–2). All analyses were performed in R version 4.2.2 (R Core Team 2022) using the packages "Openxlsx", "ExpDes.pt", and "Ggplot2".

Results

Soil management systems did not influence the results, with only the cover crops and the season of the year being significant for all variables studied. An interaction between cover crops and season was observed in the production of aboveground dry biomass (Table 1). The cover crops C1, CJ, C2, and M (10.32, 10.31, 9.13, 8.31 Mg ha^{-1}) produced the highest amounts of aboveground dry biomass in summer, while in winter, greater production was observed for C1, C2, M, and CJ (3.83, 3.27, 1.90, 1.77 Mg ha^{-1}), respectively. In both seasons, higher aboveground dry biomass production was observed in plots where cover crop mixtures were used, especially with C1, which consisted of 100% of the recommended seed rates typically used to create cover crop mixes (Table 1).

For the C/N ratio of the cover crops, no interaction was observed between cover crop species and season; only the main effect of the cover crop and season was statistically significant. In summer, the highest C/N ratio was recorded for treatment M (50.15), followed by SP, C1, C2, JB, and CJ (40.95, 20.27, 19.60, 17.36, and 17.29, respectively). In winter, the highest C/N ratio was observed for SP (64.87), followed by M, C1, CJ, C2, and JB (51.73, 34.13, 28.40, 27.96, and 19.28, respectively). Overall, higher C/N ratios were recorded during winter (37.73) compared to summer (27.60) (Table 1).

Overall, nutrient concentrations were significantly influenced by both the season and the cover crop species (Table 2). For nitrogen (N) content, seasonal variation was evident, with higher concentrations observed during the summer (17.61 g kg^{-1}) compared to the winter (14.71 g kg^{-1}). Significant differences

Table 1 Aboveground dry biomass and C/N ratio of cover crops in winter and summer

Cover Crops	Aboveground dry biomass of cover crops (Mg ha^{-1})		C/N ratio	
	Summer	**Winter**	**Summer**	**Winter**
SP	6.16 Aa	2.52 Aa	40.95 b	64.87 a
C2	9.13 Aa	3.27 Bb	19.60 b	27.96 b
C1	10.33 Aa	3.84 Bb	20.27 b	34.13 b
M	8.31 Aa	1.90 Bb	50.15 a	51.73 b
JB	4.01 Aa	1.70 Aa	17.36 b	19.28 b
CJ	10.34 Aa	1.78 Bb	17.29 b	28.40 b
Season effect means	$\bar{x}$= 8.05	$\bar{x}$= 2.50	$\bar{x}$= 27.60 B	$\bar{x}$= 37.73 A
Season x Cover Crop	p = 0.013 F value = 3.49		p = 0.4482 F value = 0.9763	

When the interaction was significant, uppercase letters were used to indicate the effect of season, and lowercase letters indicate significant differences for cover crops between seasons. When the interaction was not significant, main effects were evaluated in each season. *SP* Spontaneous plants, *C2* mixtures 50% rate, *C1* 100% of the recommended seeding rate for each species, *M* Millet, *JB* Jack bean, *CJ* sunn hemp. Significance level $p < 0.10$.

Table 2 Nitrogen (N), phosphorus (P), and potassium (K) content of cover crops in winter and summer

Cover Crops	N content (g kg^{-1})		P content (g kg^{-1})		K content (g kg^{-1})	
	Summer	Winter	Summer	Winter	Summer	Winter
SP	8.69 b	8.27 b	2.69 Bb	4.70 Aa	32.60	28.14
C2	21.33 b	17.96 b	2.45 Aa	2.86 Aa	25.30	28.63
C1	21.54 b	12.65 b	2.68 Aa	2.74 Aa	30.01	43.70
M	8.08 b	8.42 b	3.83 Aa	3.80 Aa	18.83	27.47
JB	21.82 b	23.48 a	2.15 Aa	2.51 Aa	24.99	37.47
CJ	24.18 a	17.50 b	2.52 Aa	2.60 Aa	24.76	26.35
Season effect means	$\bar{x}$= 17.61 A	$\bar{x}$= 14.71 B	$\bar{x}$= 2.72	$\bar{x}$= 3.20	$\bar{x}$= 26.08 B	$\bar{x}$= 31.96 A
Season x Cover Crop	p = 0.1149, F value = 1.95		p = 0.084, F value = 2.15		p = 0.2359, F value = 1.44	

When the interaction was significant, uppercase letters were used to indicate the effect of season, and lowercase letters indicate significant differences for cover crops between seasons. When the interaction was not significant, main effects were evaluated in each season. *SP* Spontaneous plants, *C2* mixtures 50% rate, *C1* 100% of the recommended seeding rate for each species, *M* Millet, *JB* Jack bean, CJ: sunn hemp. Significance level $p < 0.10$.

were also found among cover crop treatments. In the summer, the highest N concentrations were recorded in the CJ treatment, followed by C1, C2, JB, SP, and M. During the winter, the JB treatment exhibited the highest N concentration, followed sequentially by C2, CJ, C1, SP, and M (Table 2). Phosphorus (P) levels were influenced by the interaction between cover crops and the season of the year. In general, the highest levels were observed in winter (Table 2). For the cover crops, no differences in P levels were found regardless of the season, except for SP, which showed significant differences, with higher levels quantified in winter. Potassium (K) levels varied according to the season, with the highest levels observed in winter (31.96) (Table 2).

Regarding nutrient accumulation in the cover crops, a significant interaction was observed between cover crop species and season, with higher accumulations recorded in summer for all nutrients evaluated (Table 3). The greatest nitrogen (N) accumulation during summer was observed in the CJ, C1, and C2 treatments (250.33, 223.09, and 195.38 kg ha^{-1}, respectively), while the lowest N accumulation occurred in winter for the C2 and C1 treatments (57.73 and 49.55 kg ha^{-1}, respectively) (Table 3). For phosphorus (P) accumulation, a significant

Table 3 Nitrogen (N), phosphorus (P), and potassium (K) accumulated cover crops in winter and summer

Cover Crops	Accumulated *N* (kg ha^{-1})		Accumulated *P* (kg ha^{-1})		Accumulated K (kg ha^{-1})	
	Summer	Winter	Summer	Winter	Summer	Winter
SP	55.74 Aa	18.31 Aa	16.68 Aa	11.61 Aa	204.05 Aa	70.82 Bb
C2	195.38 Aa	57.73 Bb	22.68 Aa	9.95 Aa	218.01 Aa	92.61 Bb
C1	223.09 Aa	49.55 Bb	28.19 Aa	10.58 Aa	315.30 Aa	154.75 Bb
M	61.26 Aa	13.37 Aa	38.67 Aa	7.22 Bb	168.94 Aa	40.83 Bb
JB	70.52 Aa	41.98 Aa	8.75 Aa	4.18 Aa	84.25 Aa	58.25 Aa
CJ	250.33 Aa	29.64 Bb	26.32 Aa	4.33 Bb	244.39 Aa	42.98 Bb
Season effect means	$\bar{x}$= 142.72	$\bar{x}$= 35.10	$\bar{x}$= 23.55	$\bar{x}$= 7.98	$\bar{x}$= 205.82	$\bar{x}$= 76.71
Season x Cover Crop	p = < 0001, F value = 11.15		p = 0.03, F value = 2.84		p = 0.016, F value = 3.32	

When the interaction was significant, uppercase letters were used to indicate the effect of season, and lowercase letters indicate significant differences for cover crops between seasons. When the interaction was not significant, main effects were evaluated in each season. *SP* Spontaneous plants, *C2* mixtures 50% rate, *C1* 100% of the recommended seeding rate for each species, *M* Millet, *JB* Jack bean, *CJ* sunn hemp. Significance level $p < 0.10$.

interaction between cover crops and season was detected, but only for the M and CJ treatments. In this case, P accumulation was greater in summer for M, and in winter for CJ (Table 3). With respect to potassium (K), accumulation was higher in summer than in winter for the C1, CJ, C2, SP, and M treatments (315.29, 244.38, 218.00, 204.05, and 168.94 kg ha^{-1} in summer vs. 154.75, 42.98, 92.61, 70.82, and 40.82 kg ha^{-1} in winter, respectively). It is noteworthy that the C1 treatment exhibited the highest K accumulation across both seasons (Table 3).

Regarding the decomposition of cover crops during summer, a greater exponential decay was observed for the C2, SP, and CJ treatments, particularly during the first 30 days, followed by stabilization over time. This pattern was not observed for the C1, M, and JB treatments, which exhibited lower exponential decay throughout the 90-day period (Fig. 5a). In winter, decomposition showed a higher exponential decay rate, indicating a faster decomposition process for most treatments (SP, JB, C1, C2, and CJ), except for M, which showed a lower decay rate (Fig. 5b). It is worth noting that decomposition tends to be faster in summer, resulting in steeper decay curves compared to winter (Fig. 5). During summer, the decomposition rate constant (k) was highest for the C1, M, C2, PE, and JB treatments (0.0193, 0.0146, 0.0139, 0.0131, and 0.0120 g g^{-1}, respectively), corresponding to shorter half-lives (35, 47, 49, 53, and 57 days). The lowest k value was observed in the CJ treatment (0.0090 g g^{-1}), which had the longest half-life (76 days) (Table 4). In winter, the k values were highest for JB, SP, CJ, and M (0.0140, 0.0125, 0.0120, and 0.0120 g g^{-1}, respectively), with shorter half-lives (49, 55, 57, and 57 days). The lowest k values were recorded for the C1 and C2 mixtures (0.0081 and 0.0088 g g^{-1}), which corresponded to the longest half-lives (84 and 78 days), respectively (Table 4).

During summer, nitrogen (N) release from the cover crops exhibited greater exponential decay for the CJ, C1, and C2 treatments, with a faster initial release of N, as confirmed by shorter half-life values ($T^{1/2}$ of 20, 19, and 20 days) and overall higher decomposition rate constants (k = 0.0339, 0.0356, and 0.0351 g g^{-1}) (Table 5). Lower decay rates, and consequently slower decomposition, were observed for the M, FP, and SP treatments, as indicated by longer half-lives (33, 31, and 22 days) and lower k values (0.0211, 0.0227, and 0.0315 g g^{-1}). Nitrogen release followed the order M > JB > SP > CJ > C2 > C1 (33, 31, 22, 20, 20, and 19 days), indicating that N release was slower in M and faster in the mixture treatments, respectively (Table 5; Fig. 6a).

Phosphorus (P) release was faster in the C1, CJ, C2, and SP treatments, as evidenced by steeper decomposition curves (Fig. 6 b), shorter half-lives (28, 27, 25, and 22 days), and higher k values (0.0244, 0.0254, 0.0281, and 0.0320 g g^{-1}). In contrast, slower P release was observed in the M and FP treatments, identified by flatter decomposition curves, longer half-lives (37 and 33 days), and lower k values (0.0188 and 0.0209 g g^{-1}), respectively. The order of

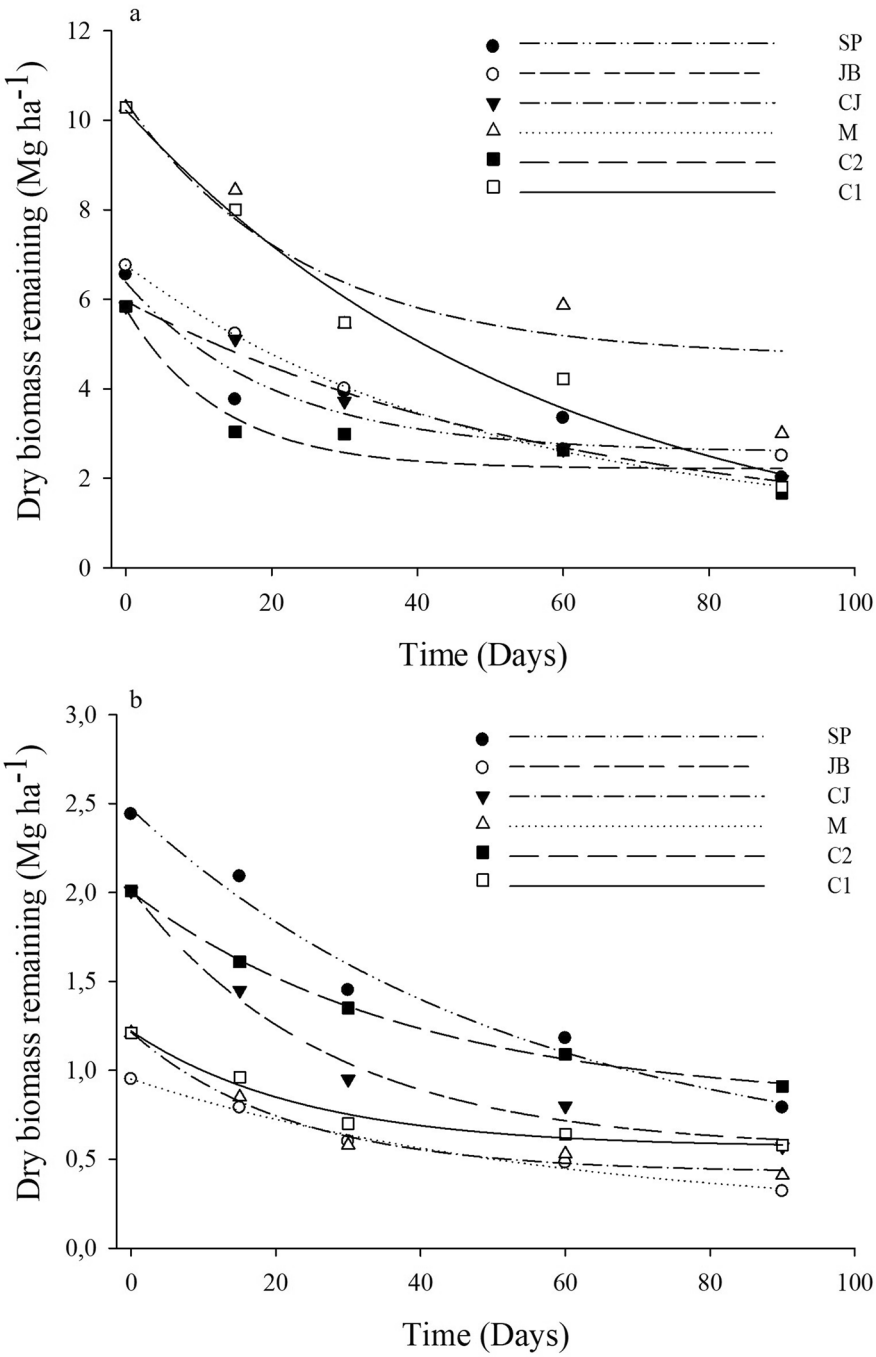


Fig. 5 Decomposition of cover crops in summer (a) and winter (b). SP: spontaneous plants, C2: mixtures 50% rate, C1: 100% of the recommended seeding rate for each species, M: millet, JB: jack bean, CJ: sunn hemp

P release was M > FP > C1 > C2 > CJ > SP, indicating intermediate release rates in the mixtures and the slowest P release in the grass species, as reflected in the $T_1/_2$ values (Table 5).

For potassium (K), a pattern similar to that observed for N and P was recorded. Faster K release was seen in the SP, C2, C1, and CJ treatments, confirmed by higher decay rates, shorter half-lives (18, 14, 12, and 13 days), and higher k values (0.0387, 0.0491, 0.0597, and 0.0543 g g^{-1}). More gradual K release was observed in the FP and M treatments, as shown by slower decay rates, longer

Table 4 Half-life time ($T^{1/2}$), decomposition constant (k) and equations representing the decomposition curves for each cover plant in the two seasons

Cover crops	Summer Cover crops			
	k (g g^{-1})	$T^{1/2}$ life (days)	Equation	R^2
SP	0.0131	53	$SP = 6.0442 + 13.5989^{(-0.1707x)}$	0.87
JB	0.0120	57	$JB = 5.9146 + 11.6152^{(-0.0742x)}$	0.98
CJ	0.0136	51	$CJ = 13.7032 + 17.1520^{(-0.1036x)}$	0.91
M	0.0110	63	$M = 5.4190 + 14.8353^{(-0.0782x)}$	0.99
C2	0.0139	50	$C2 = 5.0100 + 12.5100^{(-0.1862x)}$	0.92
C1	0.0193	36	$C1 = 5.4000 + 25.4400^{(-0.0780x)}$	0.98
Cover crops	Winter Cover crops			
	k (g g^{-1})	$T^{1/2}$ life (days)	Equation	R^2
SP	0.0125	55	$SP = 2.3700 + 4.9500^{(-0.0796x)}$	0.97
JB	0.0140	49	$JB = 1.7100 + 4.3200^{(-0.1050x)}$	0.98
CJ	0.0120	57	$CJ = 1.2300 + 2.4000^{(-0.1207x)}$	0.98
M	0.0120	57	$M = 0.9600 + 1.8900^{(-0.0763x)}$	0.98
C2	0.0088	78	$C2 = 2.7300 + 3.3000^{(-0.0879x)}$	0.99
C1	0.0081	84	$C1 = 1.7400 + 1.8900^{(-0.1109x)}$	0.98

SP Spontaneous plants, *C2* mixtures 50% rate, *C1* 100% of the recommended seeding rate for each species, *M* millet, *JB* Jack bean, *CJ* sunn hemp.

half-lives (21 and 19 days), and lower k values (0.0335 and 0.0362 g g^{-1}). The release order was FP > M > SP > C2 > C1 > CJ (Table 5; Fig. 6c).

In winter, the fastest nitrogen (N) release was observed in the CJ, C1, and C2 treatments, as confirmed by steeper decomposition curves, shorter half-lives ($T^{1/2}$ of 23, 22, and 19 days), and higher decomposition rate constants (k = 0.0299, 0.0321, and 0.0369 g g^{-1}) (Table 5; Fig. 6d). In contrast, the M, FP, and SP treatments showed lower curve slopes, indicating slower decomposition, longer half-lives (67, 32, and 25 days), and lower k values (0.0103, 0.0215, and 0.0278 g g^{-1}).

For phosphorus (P), greater curve slopes were recorded for the CJ, C1, C2, and SP treatments, with shorter $T_1/_2$ values (25, 25, 24, and 22 days) and higher k constants (0.0275, 0.0244, 0.0291, and 0.0308 g g^{-1}). The opposite pattern was observed for the M and FP treatments, which exhibited slower decay curves, indicating more gradual P release, longer $T^{1/2}$ (35 and 32 days), and lower k values (0.0195 and 0.0216 g g^{-1}) (Table 5; Fig. 6e).

In winter, a faster release of potassium (K) was observed for the C2, SP, CJ, M, FP, and C1 treatments, as indicated by steeper decay curves across all treatments and similar half-life values ($T^{1/2}$ of 24, 16, 14, 12, 12, and 12 days, respectively) and corresponding k constants (0.0287, 0.0435, 0.0502, 0.0565, 0.0584, and 0.0556 g g^{-1}). Across both seasons, the $T^{1/2}$ values for nutrient release averaged approximately 31, 27, and 15 days for N, P, and K in winter, and 24, 28, and 16 days in summer, respectively (Table 5; Fig. 6f). These values indicate that approximately 50% of the N, P, and K retained in the cover crops were released within this period following cover crop termination.

Discussion

The seasonal use of cover crops significantly influenced their agronomic performance, particularly in terms of biomass production and nutrient dynamics. The management systems did not influence the evaluated attributes, which may be related to the short duration of the experiment (four years). The first five years following the implementation of the no-tillage system are considered an adaptation phase, during which the system requires greater energy input to reach a new equilibrium and begin to express the benefits associated with its adoption compared to the conventional system (Addiscott 1995, 2010; Pinto et al. 2023). In contrast to the lack of management effects, seasonal dynamics strongly influenced aboveground dry biomass production. Comparative analysis between winter and summer seasons revealed that the highest aboveground dry biomass yields were obtained during summer, a period characterized by increased rainfall and temperatures conducive to vegetative growth. These favorable conditions led to

Table 5 Half-life ($T^{1/2}$), decomposition constant (k), and equations representing the nutrient release curves for each cover crop during the summer

Summer cover crops					
Cover crops	k ($g\ g^{-1}$) N	$T^{1/2}$ life (days)		Equation	R^2
SP	0.0315	22	$SP = 11.5416 + 185.7384e^{(-0.1779x)}$		0.99
JB	0.0227	31	$JB = 31.3989 + 211.0011e^{(-0.0446x)}$		0.91
CJ	0.0339	20	$CJ = 34.6875 + 702.8325e^{(-0.2097x)}$		0.98
M	0.0211	33	$M = 28.9348 + 165.0452e^{(-0.0848x)}$		0.99
C2	0.0351	20	$C2 = 23.3986 + 555.6014e^{(-0.1545x)}$		0,98
C1	0.0356	19	$C1 = 19.3568 + 437.1832e^{(-0.1269x)}$		0,99
P					
SP	0.0320	22	$SP = 2.3936 + 40.3564e^{(-0.1759x)}$		0.95
JB	0.0209	33	$JB = 5.6660 + 31.5940e^{(-0.0510x)}$		0.95
CJ	0.0281	25	$CJ = 6.2194 + 71.8106e^{(-0.1734x)}$		0.95
M	0.0188	37	$M = 10.6372 + 47.5628e^{(-0.0747x)}$		0.98
C2	0.0254	27	$C2 = 5.0542 + 45.0458e^{(-0.1322x)}$		0.99
C1	0.0244	28	$C1 = 7.9091 + 63.7909e^{(-0.1072x)}$		0.98
K					
SP	0.0387	18	$SP = 16.5600 + 523.9200e^{(-0.1540x)}$		0.98
JB	0.0335	21	$JB = 16.3435 + 319.2065e^{(-0.0823x)}$		0.88
CJ	0.0543	13	$CJ = 5.7719 + 760.7581e^{(-0.1945x)}$		0.99
M	0.0362	19	$M = 13.6078 + 342.6122e^{(-0.0901x)}$		0.82
C2	0.0491	14	$C2 = 7.8105 + 644.0595e^{(-0.1523x)}$		0.97
C1	0.0597	12	$C1 = 3.1500 + 675.4200e^{(-0.1159x)}$		0.94
Winter cover crops					
Cover crops	k ($g\ g^{-1}$) N	$T^{1/2}$ life (days)	Equation		R^2
SP	0.0278	25	$SP = 3.4727 + 39.0025e^{(-0.0842x)}$		0.98
JB	0.0215	32	$JB = 19.3937 + 115.9289e^{(-0.0817x)}$		0.88
CJ	0.0299	23	$CJ = 3.7202 + 51.2998e^{(-0.2139x)}$		0.99
M	0.0103	67	$M = 15.3240 + 23.6760e^{(-0.0747x)}$		0.95
C2	0.0369	19	$C2 = 7.9969 + 213.4631e^{(-0.2065x)}$		0.99
C1	0.0321	22	$C1 = 6.0911 + 104.1889e^{(-0.1630x)}$		0.99
P					
SP	0.0308	22	$SP = 1.8387 + 27.6513e^{(-0.1828x)}$		0.99
JB	0.0216	32	$JB = 1.9326 + 11.5974e^{(-0.0787x)}$		0.92
CJ	0.0275	25	$CJ = 0.7684 + 8.3816e^{(-0.1999x)}$		0.99
M	0.0195	35	$M = 2.1398 + 10.2802e^{(-0.0823x)}$		0.93
C2	0.0291	24	$C2 = 1.87992 + 24.0708e^{(-0,0879x)}$		0.99
C1	0.0244	25	$C1 = 1.9179 + 20.5521e^{(-0.2347x)}$		0.99
K					
SP	0.0435	16	$SP = 5.4000 + 267.2400e^{(-0.0923x)}$		0.88
JB	0.0584	12	$JB = 1.0500 + 201.1800e^{(-0.0856x)}$		0.87
CJ	0.0502	14	$CJ = 1.2300 + 111.5700e^{(-0.0908x)}$		0.91
M	0.0565	12	$M = 1.2000 + 193.6200e^{(-0.1217x)}$		0.98
C2	0.0287	24	$C2 = 19.5300 + 239.7300e^{(-0.1117x)}$		0.96
C1	0.0556	12	$C1 = 1.7400 + 257.5200e^{(-0.1341x)}$		0.96

SP Spontaneous plants, *C2* mixtures 50% rate, *C1* 100% of the recommended seeding rate for each species, *M* Millet, *JB* Jack bean, *CJ* sunn hemp.

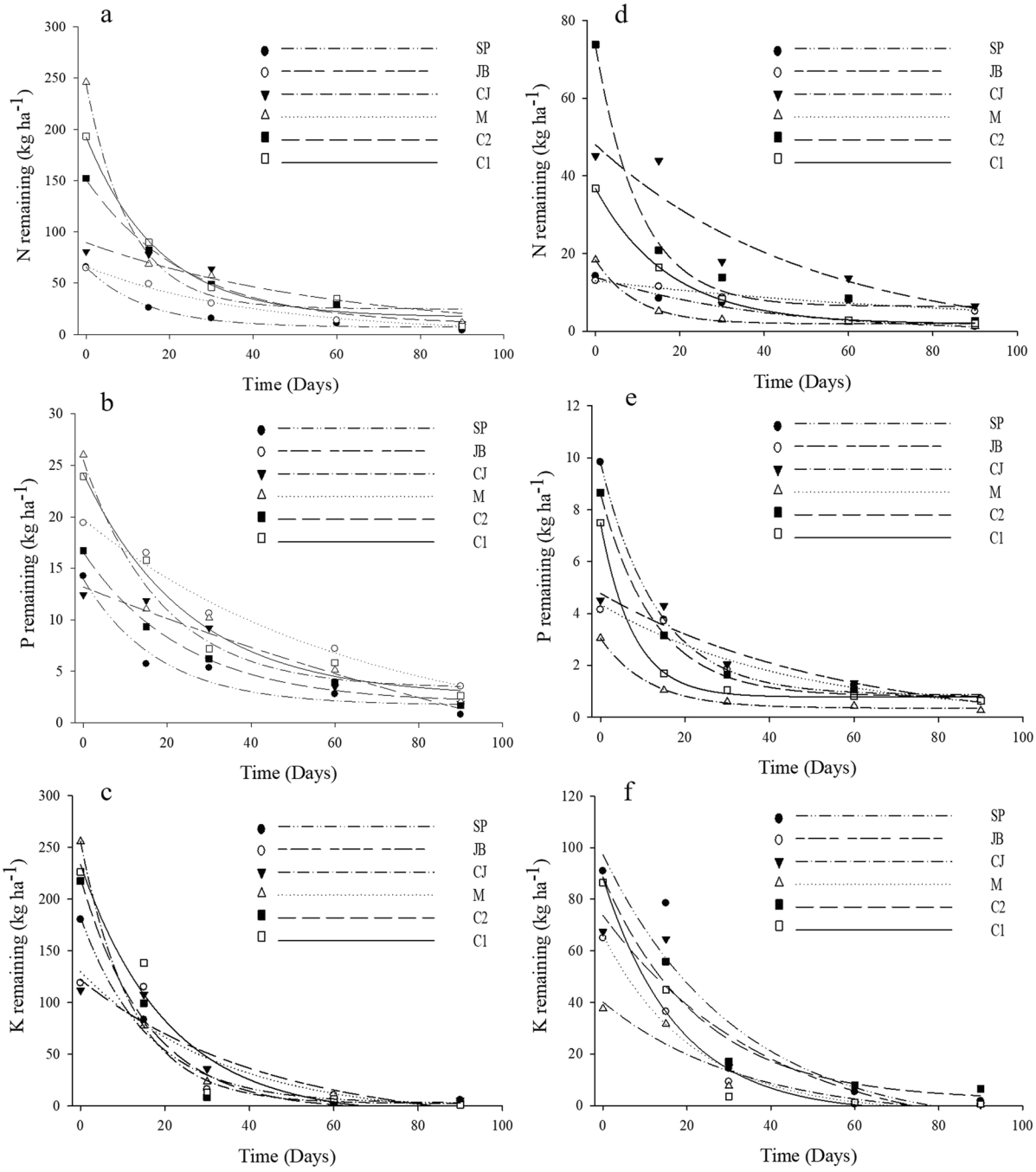


Fig. 6 Release of N, P, and K over 90 days during the summer (**a**, **b**, **c**) and winter (**d**, **e**, **f**). SP: spontaneous plants, C2: mixtures 50% rate, C1: 100% of the recommended seeding rate for each species, M: millet, JB: jack bean, CJ: sunn hemp

significantly greater biomass accumulation compared to the same cover crop species grown in winter. Monocultures established during spring/summer benefited from elevated temperature and precipitation, which supported the robust growth of species adapted to these conditions (Vanolli et al. 2024).

In summer, cover crops generally produced aboveground dry biomass levels ≥ 5–6 Mg ha^{-1}, which is

considered adequate for effective soil cover and erosion prevention (Alvarenga et al. 2001; Menezes et al. 2009). In contrast, during winter, cover crop mixtures outperformed monocultures in aboveground dry biomass production. This suggests that species mixtures (or "cocktails") offer a viable strategy for maintaining soil cover in less favorable conditions. Grasses contributed to the persistence of surface residue, while legumes enhanced nutrient cycling due to their biological nitrogen fixation capacity (Hunter et al. 2019).

Cover crops play a critical role in nutrient extraction and cycling, with seasonal variation influencing both nutrient concentration and accumulation. In summer, the legume CJ (Crotalaria juncea) demonstrated high nitrogen content (20–30 g kg^{-1}) and accumulation (250–300 kg ha^{-1}). The elevated nitrogen levels are attributed to CJ's N-fixing capacity, a finding corroborated by previous studies (Perin et al. 2004; Silva et al. 2010; Soratto et al. 2012; Chagas et al. 2024). Leal et al. (2012), under similar climatic conditions in Seropédica, RJ, also reported comparable N concentrations and accumulations, highlighting a direct correlation between aboveground dry biomass production and nutrient accumulation.

Interestingly, higher concentrations of phosphorus (P) and potassium (K) were observed in winter. This is likely due to the increased root depth developed in response to water stress, driven by elevated abscisic acid (ABA) levels that enhance root growth (Magalhães Filho et al. 2008; Zonta et al. 2018). For P characterized by low mobility in soil nutrient uptake is strongly dependent on root system expansion (Bucher et al. 2018). Ecological succession studies show that, as natural vegetation progresses, both total and available soil phosphorus contents tend to increase, an effect associated with the development of more extensive root systems in communities stabilized over time (Zhu et al. 2021; Yu et al. 2021). This explains the significant difference observed for SP, which exhibited higher P content in winter, as these plants have been established in the area for a longer period and likely possess a more developed root system. Furthermore, under low-growth conditions typical of winter, nutrient concentration may increase due to dilution effects being minimized (Borges and Caldas 2004).

The highest N, P, and K accumulations were observed in the CJ, C1, C2, and M treatments, which were also those with the highest aboveground dry biomass yields. As cover crop residues decompose, the accumulated nutrients are progressively released into the soil. The decomposition rate is influenced in large part by the residue's carbon to nitrogen (C/N) ratio. High C/N ratios common in grasses can slow decomposition by limiting microbial access to nitrogen (Perin et al. 2004; Weil and Brady 2017), thereby extending residue persistence and soil cover, as observed for M in both seasons.

Conversely, leguminous cover crops such as JB and CJ, characterized by low C/N ratios, decomposed more rapidly, promoting nutrient cycling. The seasonal variation in C/N ratios was also evident, with higher ratios in winter, largely due to reduced N content, which delayed decomposition and extended residue persistence under lower temperature and moisture conditions. In contrast, leguminous residues under warmer summer conditions decomposed more rapidly due to both favorable weather and inherently lower C/N ratios (Teixeira et al. 2009).

In winter, monocultures such as JB exhibited faster decomposition, as indicated by lower half-life ($T^{1/2}$) values and higher decay rate constants (k), although they also produced less biomass due to limited rainfall. This rapid decomposition led to reduced residue persistence on the soil surface. Meanwhile, species mixtures, which yielded more biomass, showed longer $T^{1/2}$ values (84 and 78 days), confirming that greater biomass extends the duration of surface cover an outcome consistent with findings by (Pacheco et al. 2011).

During summer, CJ again stood out for its high biomass production and prolonged residue persistence, contributing to improved soil cover. Notably, management recommendations for cover crops must consider seasonal context. While leguminous monocultures are suitable for summer, winter conditions favor the use of diverse species mixtures to compensate for reduced growth and ensure adequate ground cover (Weiler et al. 2019).

Decomposition was significantly slower in winter than in summer, attributable to lower precipitation and temperature. These conditions reduce microbial activity, thereby inhibiting organic matter breakdown (Boer et al. 2008; Torres et al. 2015; Petraglia et al. 2019). Nutrient release dynamics also differ by season. Mixtures released N, P, and K more rapidly than monocultures, while millet released nutrients more gradually because of its high C/N ratio and longer $T^{1/2}$ values.

The nutrient release patterns reflected the biochemical characteristics of the cover crops. Pearl millet's gradual decomposition led to slower nutrient release, whereas mixtures with intermediate C/N ratios balanced soil cover persistence and nutrient availability. These findings align with previous research suggesting that intermediate C/N ratios favor moderate decomposition rates, maintaining surface residue while enhancing nutrient cycling for subsequent crops (Doneda et al. 2012; Torres et al. 2021)

Across both seasons, average nutrient $T^{1/2}$ values were approximately 31, 27, and 15 days in winter, and 24, 28, and 16 days in summer for N, P, and K, respectively. Torres et al. (2021) reported similar values for K, which is rapidly released due to its high mobility and lack of structural binding within plant tissues (Meurer et al. 2018). Other studies also confirm the fast release kinetics of K (Viola et al. 2013; Torres et al. 2021). These results underscore the importance of strategically selecting cover crop species and mixtures based on their physiological traits and seasonal performance to optimize nutrient cycling and residue management in agroecosystems. Incorporating species mixtures appears to be particularly advantageous in winter, promoting longer residue persistence while simultaneously enhancing nutrient availability for subsequent cropping cycles.

Conclusion

The study demonstrated that the management systems did not significantly influence the evaluated variables, possibly due to the relatively short experimental period (four years).

Cover crop species and season significantly influenced aboveground dry biomass production and nutrient accumulation, particularly for the C1, CJ, C2, and M treatments across both summer and winter seasons.

Cover crop mixtures combining CJ, JB, and M are recommended for winter, as they resulted in higher biomass production and slower decomposition rates, contributing to prolonged soil cover.

The production and decomposition dynamics of cover crop biomass varied according to the season, with CJ being best suited for summer conditions, while C1 and C2 performed better in winter.

These findings highlight the importance of selecting appropriate cover crop species for each season, reinforcing the need for further research to optimize cover crop use in seasonal agroecosystems.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval All authors have read, understood, and complied with all requirements regarding the ethical responsibility of the journal and are aware that, with minor exceptions, no changes may be made in authorship after submission of the article.

Consent to publish The authors consent to the case manuscript being submitted to and published in the journal.

Conflicts of interest The authors declare no competing interests.

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