Índices de qualidade do resíduo vegetal: uma abordagem metodológica para a avaliação de plantas de cobertura de verão em climas tropicais

Victor de Oliveira Dias, Giovana Ghisleni Ribas, Maria Eduarda Almeida Souza, Douglas Martins de Santana, Juan Piero Antonio Raphael, Carlos Armênio Khatounian, José Laércio Favarin

https://doi.org/10.1590/SciELOPreprints.12479

Submetido em: 2025-07-02
Postado em: 2025-07-04 (versão 1)
(AAAA-MM-DD)

Plant residue quality indices: a methodological approach for evaluating summer cover crops under tropical climates

Índices de qualidade do resíduo vegetal: uma abordagem metodológica para a avaliação de plantas de cobertura de verão em climas tropicais

[1*]Victor de Oliveira Dias (https://orcid.org/0009-0002-5188-5251)

[1]Giovana Ghisleni Ribas (https://orcid.org/0000-0001-5546-1291)

[1]Maria Eduarda Almeida Souza (https://orcid.org/0009-0000-7991-6350)

[1]Douglas Martins de Santana (https://orcid.org/0000-0002-5158-745X)

[1]Juan Piero Antonio Raphael (https://orcid.org/0000-0001-7143-623X)

[1]Carlos Armênio Khatounian (https://orcid.org/0000-0002-4642-6635)

[1]José Laércio Favarin (https://orcid.org/0000-0003-0556-9397)

[1]Departament of Crop Science, "Luiz de Queiroz" College of Agriculture (ESALQ), University of São Paulo (USP), Piracicaba-SP, 13418-900, Brazil;

* Correspondence: victordeoliveiradias@usp.br and gribas@usp.br

ABSTRACT:

The success of conservation agriculture in tropical environments depends on crop rotations that ensure adequate quantity and quality of phytomass for persistent soil cover. The objective of this study was to evaluate biomass decomposition and nitrogen (N) release by summer cover crop species, employing distinct indices to assess their plant residues in terms of accumulated N release (NAR) and remaining dry matter (RDM). The experiment was conducted on a "Nitossolo Eutrófico" at the "Luiz de Queiroz" College of Agriculture, in a randomized block design with five treatments and four replicates. Treatments consisted of plant residues from sunn hemp (*Crotalaria juncea* L.), jack bean (*Canavalia ensiformis* (L.) DC.), Congo grass (*Urochloa ruziziensis* L.), pearl millet (*Pennisetum glaucum* L.), and maize (*Zea mays* L.). Biomass decomposition and N release were assessed using nylon litter bags, with samplings conducted at 15, 30, 60, and 90 days after crop termination. The legume species exhibited the highest N release rates, while among grasses, pearl millet had the highest NAR and the greatest RDM after 90 days. A significant linear correlation was found between the Plant Residue Quality Index (PRQI) and the rates of biomass decomposition and N release. At the same time, the Residual Biomass Quality Index (RBQI) identified tropical forages as more efficient in balancing NAR and RDM throughout the experimental period. These findings can support cover crop selection in tropical rotations aiming at synchronized N release and persistent soil cover.

Key-words: Nitrogen mineralization, Biomass decomposition rate, No-till system, Carbon-to-nitrogen ratio, Crop rotation

RESUMO:

O sucesso da agricultura conservacionista em ambientes tropicais depende de rotações de cultura que forneçam fitomassa sobre o solo em quantidade e qualidade suficientes para assegurar sua cobertura contínua. O objetivo deste estudo foi avaliar a decomposição da biomassa e a liberação de nitrogênio (N) de espécies de plantas de cobertura de verão, empregando-se índices distintos para qualificação de seus resíduos vegetais em termos de liberação cumulativa de N (LCN) e massa seca remanescente (MSR). O experimento foi conduzido em um Nitossolo Eutrófico na Escola Superior de Agricultura “Luiz de Queiroz”, em blocos casualizados com cinco tratamentos e quatro repetições. Os tratamentos foram constituídos de resíduos vegetais de cinco espécies: crotalária-júncea (*Crotalaria juncea* L.), feijão-de-porco (*Canavalia ensiformis* (L.) DC.), braquiária ruziziensis (*Urochloa ruziziensis* L.), milheto (*Pennisetum glaucum* L.) e milho (*Zea mays* L.). A decomposição de biomassa e a liberação de N foram avaliados por meio de sacolas de náilon, com coletas aos 15, 30, 60 e 90 dias após o manejo das espécies. As leguminosas apresentaram as maiores taxas de liberação de N, enquanto, entre as gramíneas, o milheto apresentou os maiores valores de LCN e de MSR ao final de 90 dias. Foi observada correlação linear significativa entre o índice de qualidade do resíduo vegetal (IQRV) e as taxas de decomposição de biomassa e taxa de liberação de N. Simultaneamente, o índice de qualidade da biomassa residual (IQBR) permitiu distinguir as forrageiras tropicais como mais eficientes em equilibrar a LCN e a MSR ao longo do período experimental. Esses resultados podem subsidiar a escolha de plantas de cobertura em rotações tropicais visando à liberação sincronizada de N e à manutenção da cobertura do solo.

Palavras-chave: Mineralização de nitrogênio, Taxa de decomposição de biomassa, Sistema plantio direto, Relação carbono-nitrogênio, Rotação de culturas

1. INTRODUCTION

The success of conservation agriculture in tropical environments depends on crop rotations that ensure adequate quantity and quality of phytomass for persistent soil cover. High-quality mulch plays a critical role in reducing water loss through evaporation (Chang et al., 2023), thereby contributing to the development of production systems more resilient to the effects of climate change (Souza et al., 2025). From this perspective, the integration of cover crops (CC) species into rotation systems has been proposed as an effective strategy to achieve these objectives (Rigon; Franzluebbers & Calonego, 2020). These plants offer several advantages, including the diversification of soil microorganisms, nutrient cycling, and the provision of substantial amounts of nitrogen (N) to cash crops (Hahn et al., 2024).

The decomposition and nutrient release from crop residues are regulated by both intrinsic and extrinsic factors inherent to the plant material. Intrinsic factors include the carbon-to-nitrogen (C/N) ratio, lignin content, and polyphenol concentration, which directly influence residue quality (Canalli et al., 2020; Tian, Brussaard & Kang, 1995; Weiler et al., 2022). These chemical attributes interact with extrinsic factors such as climatic conditions, soil microbial activity, and the phenological stage at termination (e.g., flowering or grain-filling), collectively determining decomposition rates, as well as N immobilization and mineralization from plant residues (Keene et al., 2017; São Miguel et al., 2018). Consequently, litter decomposition patterns vary among species from different botanical families, such as Fabaceae and Poaceae, which typically exhibit contrasting effects on soil cover maintenance and N cycling (Chang et al., 2023; Saadat et al., 2025; Hahn et al., 2024; Kim et al., 2025).

Despite the widely recognized benefits of CC, uncertainty remains among technicians and farmers regarding the most suitable species for rotation systems (Alonso-Ayuso et al., 2020). Considering the predominant no-tillage production system in the Brazilian Midwest, based on the succession of soybean (*Glycine max* (L.) Merrill) and maize (*Zea mays* L.), an optimal CC could be characterized by its capacity to produce the highest possible amount of residual dry matter (RDM) on the soil surface, thereby minimizing water loss through evaporation, and to release the maximum amount of N, a major yield gap to cash crops (Cassol et al., 2023; Tittonell & Giller, 2013). In this regard, Souza et al. (2025) emphasize the crucial role of CC with these characteristics as key components of climate-smart agriculture, essential for ensuring yield and soil health production systems of the Brazilian “Cerrado”.

Similarly, Cassol et al. (2023) proposed a conceptual model for production systems in southern Brazil, in which elevated values of a residual biomass quality index (RBQI) indicate CC that achieve an optimal balance between N release and biomass persistence on the soil surface. Consequently, RBQI could serve as a valuable tool for evaluating the equilibrium in the provision of these ecosystem services, aiding in the selection of suitable CC for tropical rotation systems. Additionally, this index may serve for assessing the extent of conservation practices adopted by farmers in Brazilian “Cerrado” agriculture, encouraging the inclusion of CC species during the window between the harvest of off-season maize and before soybean sowing (Possamai et al., 2022; Saadat et al., 2025; Telles et al., 2020).

However, few studies have assessed the quality of plant residues from CC adapted to tropical environments. Traditional indices, such as the Plant Residue Quality Index (PRQI) (Tian, Brussaard & Kang, 1995), were initially developed to link the chemical traits of plant residues (mainly from agroforestry and forage species) to their decomposition and N release, but without specific validation for CC. More recently, the Residue Biomass Quality Index (RBQI) was introduced for evaluating residue quality in winter CC under subtropical climates (Cassol et al., 2023). Thus, we hypothesized that both indices could also be reliably applied to summer CC in tropical regions, offering consistent predictions of biomass breakdown and N release. In this context, the present study aimed to test the applicability of PRQI and RBQI for summer CC species, focusing on: (i) biomass decomposition dynamics, (ii) N release to subsequent cash crops, and (iii) initial chemical characteristics of the residues.

2. MATERIALS AND METHODS

2.1 Experimental site and design

This study was conducted between September 2024 and February 2025, in the experimental area of the Crop Science Department (LPV) at the "Luiz de Queiroz" College of Agriculture (ESALQ), University of São Paulo (USP), in Piracicaba-SP, Brazil (22° 42' 17.53" S, 47° 38' 8.33" W, 553 m). The region's climate is classified as tropical (Cwa) according to the Köppen system, with an average annual precipitation of 1328 mm and a mean temperature of 26.2°C (Alvares et al., 2013). This climate has two distinct seasons: a warm, rainy summer (October-March) and a cooler, dry winter (April-September). Weather data were recorded by an automatic station located 1.3 km from the experimental site (Figure 1).

The soil was classified as a “Nitossolo Eutrótico Típico de textura argilosa” (Santos et al., 2018), and its chemical properties were assessed in the 0-0.20 m layer prior to CC sowing, following the methodology of Raij et al. (2001): Ca = 108.2 mmolC dm^{-3}; Mg = 29.4 mmolC dm^{-3}; K = 8.7 mmolC dm^{-3}; Al = 0.0 mmolC dm^{-3}; H + Al = 24.4 mmolC dm^{-3}; P = 16.2 mg dm^{-3}; S = 146 mg dm^{-3}; Cu = 5.9 mg dm^{-3}; Fe = 22.8 mg dm^{-3}; Mn = 15.7 mg dm^{-3}; Zn = 2.1 mg dm^{-3}; B = 0.36 mg dm^{-3}; pH $CaCl_2$ = 5.45; m = 0.00; MO = 26 mg dm^{-3}; CTC = 170.7 mmolC dm^{-3}; SB = 146.3 mmolC dm^{-3}; V = 86%.

The experiment was arranged in a randomized block design with four blocks, each containing one replicate (litter bag) of five CC species. Residue decomposition and N release were evaluated at four sampling periods (15, 30, 60, and 90 days after species termination), totaling 80 experimental units (5 species × 4 blocks × 4 sampling times). To produce the plant residues, all CC species were manually sown (without base fertilizer) on September 2, 2024. Sowing densities and row spacings were defined according to Lima-Filho et al. (2023).

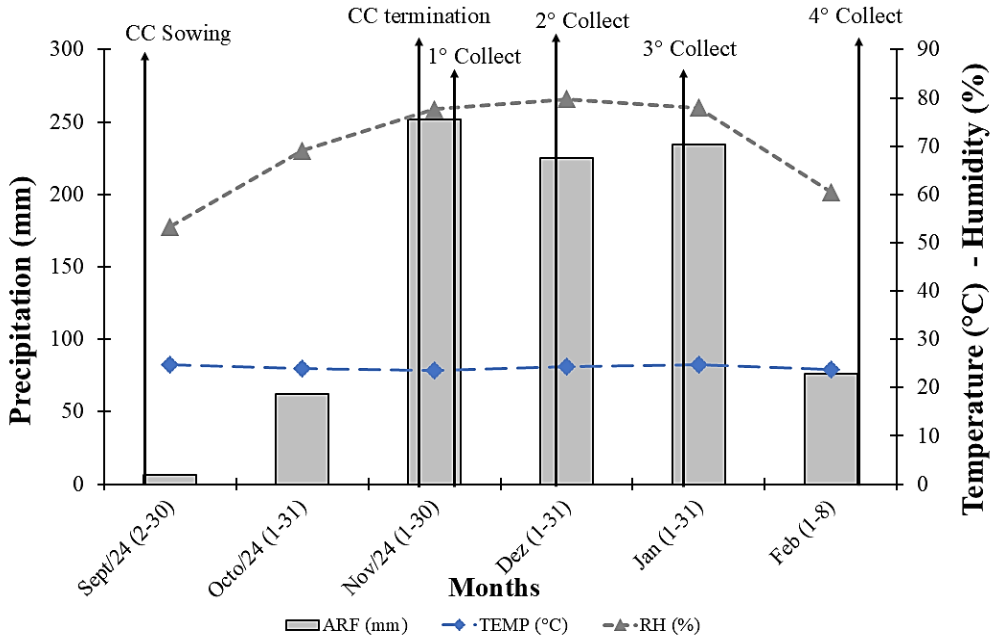

Figure 1: Accumulated rainfall (ARF), mean air temperature (TEMP), and mean relative humidity (RH), recorded in the automatic weather station of ESALQ/USP during the experimental period.

The experimental area management included manual weeding up to 30 days after CC sowing (DAS), along with supplemental sprinkler irrigation applied exclusively during September, in response to low rainfall recorded in that month (Figure 1). Irrigation was performed daily for 10 minutes, delivering an estimated water of approximately 0.6 mm per event, based on an application rate of 3.6 mm h^{-1} for conventional sprinkler systems.

2.2 Biomass parameters

At 68 DAS (November 10, 2024), all CC were terminated with a knife roller and left over the soil as mulch. Shoot fresh matter (SFM) was determined by collecting five 0.25 m^2 samples per specie and weighing them in the field. Samples were then oven-dried at 65°C for 72 h to obtain shoot dry matter (SDM). The initial chemical composition of the CC was analyzed descriptively after grinding the material (0.5 mm sieve), using a representative mixture of stems, leaves, and flowers in the same field proportions produced by the species (Table 1).

Carbon content was standardized at 40% of dry matter, an average value well supported in the literature for its consistency and broad applicability to tropical grasses and legumes used as green manure (Lovato et al., 2004; Medina et al., 2013; Palm et al., 2001). Total soluble polyphenols were determined using the Folin-Denis method (Anderson & Ingram, 1996; Gama-Rodrigues et al., 2007), while lignin content was analyzed following the sequential procedure described by Van Soest, Robertson, & Lewis (1991). N determination was performed according to the methodology proposed by Tedesco et al. (1995).

Table 1: Average (*n* = 5) of biomass production of cover crops terminate at the flowering and vegetative stages (68 DAS) and initial chemical characteristics of the plant residues. Piracicaba-SP, Brazil.

Species	Shoot matter				Chemical characteristics		
	FM	DM	C	N	C/N	LIG	POL
	-------- (Mg ha^{-1}) --------			kg ha^{-1}	---	------- (%) ------	
Pennisetum glaucum**	43.0	14.1	5.6	217.0	25.9	4.8	0.4
Urochloa ruziziensis*	27.8	9.8	3.9	138.7	28.3	2.4	1.2
Crotalaria juncea**	32.5	8.5	3.4	245.4	13.9	3.5	0.6
Zea mays*	16.1	4.9	2.0	61.8	32.3	7.6	0.3
Canavalia ensiformis*	14.4	2.8	1.1	104.8	10.8	2.7	2.1

FM: Fresh matter; DM: Dry matter; C: Carbon; N: Nitrogen; C/N: Carbon/Nitrogen ratio; LIG: Lignin; POL: Total soluble polyphenols; (*) Species terminated at the vegetative and (**) at the flowering stage. Values in this table represent total field biomass and N content, which differ from day 0 litter bag values due to the use of smaller, standardized, and proportionally scaled subsamples following the litter bag methodology.

The decomposition and N release from the CC plant residues were evaluated using the litter bag method, as outlined by Keuskamp et al. (2013) and Cassol et al. (2023). Nylon litter bags with a mesh size of 4 mm and dimensions of 16×20 cm (0.032 m²) were used, permitting the passage of microorganisms, worms and other invertebrates. The initial fresh matter (IFM) placed in the litter bags was proportional to the SFM of each species, aiming to evaluate the quantity and quality of the CC residues produced for lasting soil cover and N release (Eq. 1).

$$IFM\ (\frac{SFM}{\text{"litter bag"}}) = (SFM\ \text{kg}\ ha^{-1}/10{,}000\ m^2) \times 0{,}032\ m^2 \qquad (1)$$

It is known that pre-drying plant residues before decomposition experiments can alter decomposition rates and delay N release during the initial evaluation period (Doneda et al., 2012; Thapa et al., 2022). To mitigate this effect, the equivalent dry matter (EDM) of each species' IFM was determined by drying four samples at 65 °C for 72 hours, with subsequent N content (ENC) calculated by Tedesco et al. (1995). Additionally, following the approach adopted by Saadat et al. (2025), fresh plant residues were directly placed in nylon mesh litter bags to better simulate field conditions. To further enhance representativeness, the same fresh proportions of leaves, stems, flowers, and branches observed in the field were maintained and conditioned within the litter bags, as recommended by Mangaravite et al. (2023).

Thus, immediately after the CC termination, litter bags containing the fresh plant residues were evenly distributed across the soil surface within the four experimental blocks. The collection times were set at 15, 30, 60 and 90 days after CC termination (DAT), with four bags per species retrieved at each interval. The evaluation period was based on previous studies, which employed durations of 90 to 120 days (Sodré-Filho et al., 2024; Torres et al., 2021; Thapa et al., 2022). Decomposition degree days (DDD) were calculated according to Singh et al. (2020), to normalize time based on daily air temperature (Eq. 2):

$$DDD = [(T_{max} + T_{min})/2] - T_{base} \tag{2}$$

where Tmax and Tmin are daily maximum and minimum air temperature, respectively, and Tbase is the base temperature according to McMaster & Wilhelm (1997). For days when Tmax or Tmin air temperature was less than Tbase, the Tmax or Tmin was equal to Tbase. For days when Tmax was greater than 30°C, it was used the value of 30°C.

After retrieval, the bag contents were manually sorted to remove soil particles and organisms, then dried in an oven at 65°C until reaching a constant mass to obtain the RDM. The decomposition rate (K) and nitrogen release rate (K_N) of the CC plant residues were calculated from the values of RDM and remaining nitrogen content (RN) obtained at each collection period, which were adjusted to the exponential model (Eq. 3) proposed by Thomas & Asakawa (1993), using the Sigma Plot© Software (version 2014).

$$x_t = x_0.\epsilon^{-kt} \tag{3}$$

where: xt = dry biomass (g) or nitrogen content (g kg^{-1}) of the plant residue remaining on the soil surface after t days; x_0 = dry biomass (g) or nitrogen content (g kg^{-1}) of the plant residue packed inside the litter bag on day zero; t = time in days and K = decomposition rate or nitrogen release rate (K_N). The half-life of CC residues, indicating the time required for half of the initial material to decompose and release half of the initial N content, was calculated using the decomposition (K) and nitrogen release (K_N) rates (Eq. 4).

$$T_{1/2} \ and \ N_{1/2} \ = \ln(2)/kt \tag{4}$$

where: $T_{1/2}$ = plant residue half-life; $N_{1/2}$ = nitrogen release half-life; t = time in days; K = biomass decomposition rate or nitrogen release rate (K_N) obtained from fitting the non-linear model. The nitrogen accumulated release (NAR), in Kg ha^{-1}, was measured according to Doneda et al. (2012), by analyzing the content of this nutrient in the initial dry matter contained in the litter bags and on each collection date. The methodology for determining the N content in the plant residues was also carried out according to Tedesco et al. (1995).

2.3 Calculation of plant residue quality indices

Two methodologies were used to determine the quality of the summer CC plant residues. The approach proposed by Cassol et al. (2023) relies on the Residual Biomass Quality Index (RBQI), a tool based on the Remaining Dry Mass Index (RDMI) on the soil surface and the Nitrogen Release Index (NRI) after the species have been managed for some period. In this way, RBQI values classify the quality of CC residues on a scale ranging from 0 to 1, where a higher value corresponds to a better balance between two ecosystemic services: N release and the permanence of crop residues on the soil surface (Eq. 5).

$$RBQI \ = RDMI \ \times NRI \tag{5}$$

To obtain the RDMI, the highest RDM value among the CC evaluated was set at 100%, as the ideal condition of soil coverage by the crop residues at the end of the 90-day evaluation. Similarly, NRI was determined based on the highest NAR value among the CC evaluated, which was defined as 100%, representing the ideal condition of N release by the crop residues at the end of the evaluation period. To compare the results obtained in determining RBQI, the index proposed by Tian, Brussaard & Kang (1995) was also analyzed descriptively (Eq. 6).

$$PRQI = \left[1/\left(a \times \frac{C}{N} + b \times Lignin + c \times Polyphenols\right) \times 100\right] \quad (6)$$

where: PRQI = Plant Residue Quality Index; a (0.423), b (0.439), and c (0.138) are coefficients representing the relative contribution of the C/N ratio, lignin content (%), and polyphenol concentration (%) to the quality of the plant residues, respectively.

2.4 Statistical analyses

After applying square root transformation ($\sqrt{\boldsymbol{x}}$), the dataset met the assumptions of normality (Lilliefors test, $p > 0.05$, “nortest package”) and homogeneity of variances (Levene’s test, $p > 0.05$, “car package”). Subsequently, ANOVA was conducted ($p < 0.05$), followed by Tukey’s test at 5% significance for mean comparisons within each sampling time (15, 30, 60, and 90 days), using the “agricolae package”. Additionally, effect size (η^2) was estimated for each sampling period using the “effectsize package”, providing a complementary interpretation to the *p*-values (Cohen, 1988). All statistical analyses were performed in RStudio© (4.2.2), while regression models describing decomposition and N release dynamics, and the relationship between PRQI and the kinetic parameters K and K_N, were fitted in SigmaPlot© (version 2014).

3. RESULTS AND DISCUSSION

3.1 Cover crops residual dry matter and decomposition

Dry matter (DM) loss over time varied significantly among treatments ($p < 0.01$ to $p < 0.05$), both in absolute terms (Mg ha^{-1}) and percentage, reflecting distinct decomposition dynamics among species (Table 2). For instance, 15 days after CC termination, jack bean (1.25 Mg ha^{-1}) and sunn hemp (2.97 Mg ha^{-1}) exhibited lower remaining dry matter (RDM) compared to Congo grass (4.84 Mg ha^{-1}) and pearl millet (5.94 Mg ha^{-1}). Thus, by the end of 30 days, only pearl millet maintained soil cover above 4.00 Mg ha^{-1}, a level of mulch considered effective for erosion control (Campos et al., 2011; Machado et al., 2001).

Table 2: Mean values ($n = 4$) of remaining dry matter (RDM) from the decomposition of summer cover crop plant residues at each sampling period. Piracicaba-SP, Brazil.

Species	Time (days)				
	0	15	30	60	90
	Percentage of remaining dry matter (% - g)				
Zea mays	100	56 a	42 a	36 a	29 a
Pennisetum glaucum	100	49 b	36 b	29 b	22 b
Urochloa ruziziensis	100	42 b	33 b	25 b	19 b
Crotalaria juncea	100	38 c	30 c	22 c	14 c
Canavalia ensiformis	100	35 c	26 c	17 c	11 c
CV (%)	0.0	17.72	23.09	27.69	32.42
p-value	--	< 0.001	0.005	0.030	0.030
$\eta2$	--	0.50**	0.45**	0.40**	0.35**
	Remaining dry matter (Mg ha^{-1})				
Pennisetum glaucum	12.06	5.94 a	4.38 a	3.59 a	2.75 a
Urochloa ruziziensis	11.50	4.84 a	3.80 a	2.88 a	2.19 a
Crotalaria juncea	7.90	2.97 b	2.34 b	1.72 b	1.09 b
Zea mays	4.66	2.59 b	1.97 b	1.66 b	1.25 b
Canavalia ensiformis	3.62	1.25 c	0.94 c	0.63 c	0.42 c
CV (%)	29.32	31.26	32.96	33.07	36.08
p-value	--	< 0.001	< 0.001	< 0.001	< 0.001
$\eta2$	--	0.50**	0.45**	0.35**	0.30**

Means followed by the same letter in the same column do not differ significantly according to Tukey's test at the 5% significance level within the same evaluation period. CV (%): coefficient of variation. *p*-value: probability associated with the F-test from analysis of variance (ANOVA). η^2: effect size, indicating the proportion of variance explained by the quantity and quality of the summer cover crops plant residues (treatments) at each sampling time; **values > 0.14 represent a large treatment effect.

Although effect size values remained statistically significant throughout the evaluation period ($\eta2 > 0.14$), indicating a consistent treatment effect, their gradual decline over time (reaching 0.35 at 90 days) suggests that the initial influence of residue quantity and quality on decomposition and N release became less evident as the process advanced (Cohen, 1988). This reduction likely reflects the influence of climatic variables, such as air temperature, relative humidity, and rainfall, on decomposition dynamics during the later stages (Figure 1).

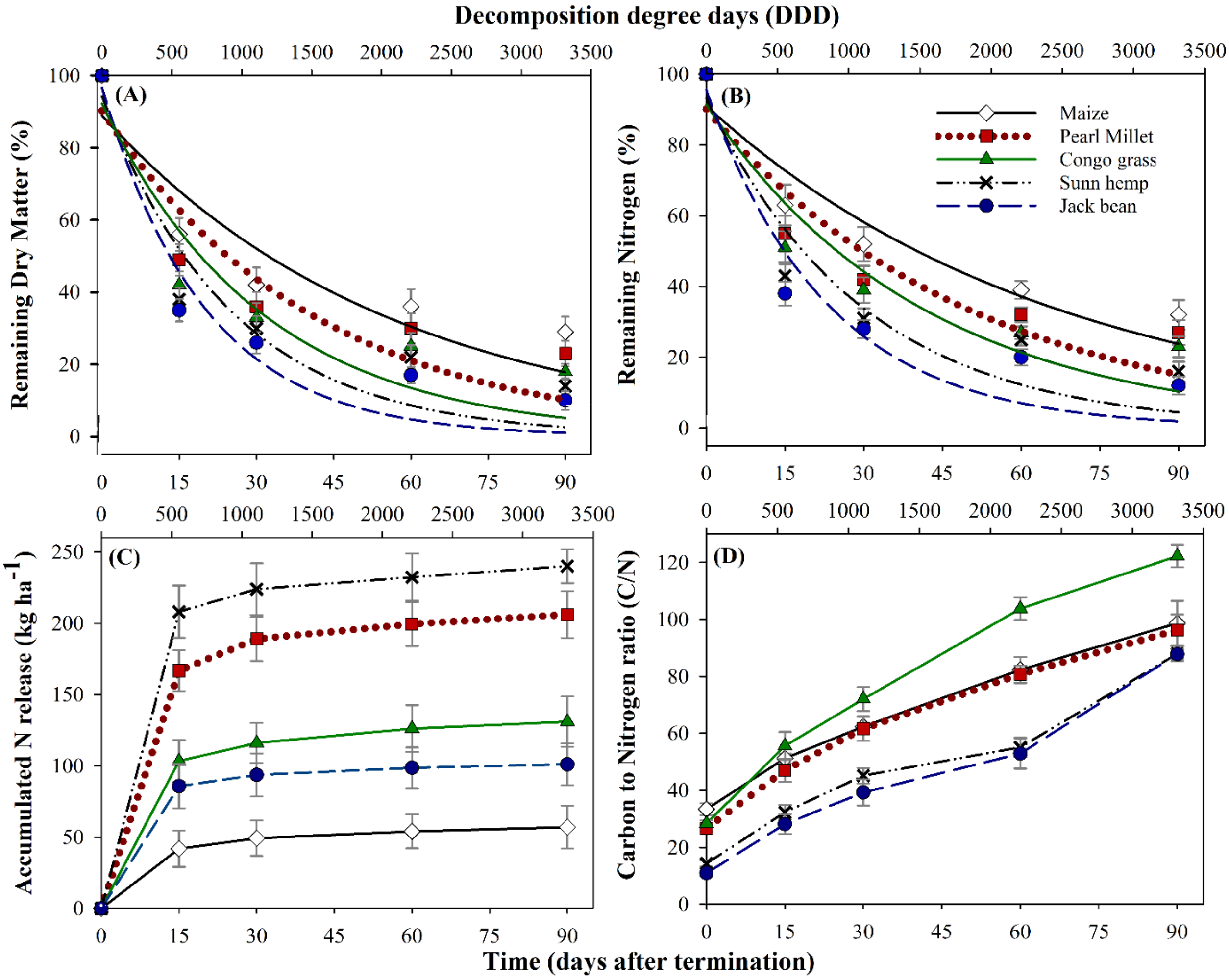

Figure 2: Percentage of remaining dry matter (A); Percentage of remaining Nitrogen (B); Accumulated Nitrogen release (kg ha^{-1}); and (C) Evolution of the Carbon/Nitrogen (C/N) ratio (D). Points represent the mean of the four blocks ($n = 4$) and vertical bars indicate the standard error of the mean. Superior x-axis indicates the decomposition degree days (DDD). Piracicaba-SP, Brazil.

Forage grasses consistently exhibited higher RDM values throughout the entire experimental period, reinforcing their potential for persistent soil cover. In this regard, 90 days after CC termination, Congo grass and pearl millet retained 2.19 Mg ha^{-1} and 2.75 Mg ha^{-1} of mulch over the soil, respectively. In contrast, the rapid biomass decomposition observed for legumes (Figure 2A; Table 2) can be attributed to their low initial C/N ratios and inferior lignin contents (Table 1), corroborating previous studies that identify these factors as critics in determining the susceptibility to DM loss and N release from CC plant residues (Cotrufo et al., 2015; Doneda et al., 2012; Thapa et al., 2022; Torres et al., 2021).

However, the C/N ratio is a general indicator that represents the total plant biomass, without distinguishing tissue fractions or organs with different chemical properties (Canalli et al., 2020; Weiler et al., 2022). Accordingly, as more labile compounds (e.g., sugars and free amino acids) present in leaves and flowers are decomposed, the C/N ratio tends to increase, likely due to the relative predominance of recalcitrant components (e.g., lignin, cellulose, and polyphenols) in stems and branches (Figure 2D). This response may partially explain the biphasic decomposition and N release dynamics observed in this study (Figure 2C), characterized by an initial phase of rapid DM and N losses, potentially driven by the C/N ratio and the presence of labile compounds, followed by a slower phase, possibly influenced by the effect of recalcitrant molecules (Sodré-Filho et al., 2024; Thapa et al., 2022).

Probably, this rapid loss of DM and N within the first 15 days is likely due to the early termination of CC, conducted during the flowering and vegetative stages (Adetunji et al., 2020). According to Khatounian (2001), the phenological stage at the time of termination significantly influences biomass decomposition rates and N release from summer green manure. At this moment, plants exhibit high levels of free amino acids and soluble compounds in the cellular vacuole, along with low cellulose and lignin content in stems and leaves, as nutrients have not yet been translocated to the seeds (Otte et al., 2019; Keene et al., 2017).

From this perspective, the overall regression analysis of DM decomposition and N release for all treatments was significant at the 1% level according to the F-test ($p < 0.01$). Additionally, the K and K_N parameters, derived from the exponential regression equations, were statistically significant according to the *t*-test ($p < 0.05$). Thus, the corresponding half-live values, calculated from K, likely reflect differences in the chemical characteristics and the proportion of plant tissues present in the residues of the CC placed in the litter bags (Table 3).

Table 3: Exponential regression equations for estimating dry matter decomposition and residual nitrogen over time (90 days evaluation period) in residues of summer cover crops. Piracicaba, SP, Brazil.

Species	Remaining Dry Matter				
	Equation	K	$T_{1/2}$	R^2	*p*-value (K)
		day^{-1}	days	---	---
Canavalia ensiformis	$y = 96.69\ e^{-0.0501t}$	0.0501	14	0.92*	0.0279
Crotalaria juncea	$y = 94.31\ e^{-0.0398t}$	0.0398	17	0.88*	0.0436
Urochloa ruziziensis	$y = 92.28\ e^{-0.0320t}$	0.0320	21	0.84*	0.0489
Pennisetum glaucum	$y = 90.23\ e^{-0.242t}$	0.0242	27	0.84*	0.0486
Zea mays	$y = 89.00\ e^{-0.0179t}$	0.0179	39	0.83*	0.0448
	Remaining Nitrogen				
	Equation	K_N	$N_{1/2}$	R^2	*p*-value (K_N)
		day^{-1}	days	---	---
Canavalia ensiformis	$y = 95.56\ e^{-0.0435t}$	0.0435	16	0.91*	0.0331
Crotalaria juncea	$y = 93.24\ e^{-0.0338t}$	0.0338	20	0.88*	0.0415
Urochloa ruziziensis	$y = 91.44\ e^{-0.0242t}$	0.0242	28	0.88*	0.0338
Pennisetum glaucum	$y = 90.18\ e^{-0.0198t}$	0.0198	35	0.86*	0.0362
Zea mays	$y = 91.06\ e^{-0.0149t}$	0.0149	46	0.90*	0.0208

K: Biomass decomposition rate; $T_{1/2}$: Plant residue half-life; K_N: Nitrogen release rate; $N_{1/2}$: Nitrogen release half-life; R^2: Adjustment coefficient of determination for estimating K or K_N; (*) Indicates that the overall regression model was significant at the 1% level according to the F-test ($p < 0.01$); *p*-value: Refers to the significance of the K or K_N coefficient, a component of the exponential regression equation, assessed by the *t*-test ($p < 0.05$).

For example, jack bean and sunn hemp exhibited the highest K values (0.0501 and 0.0398 day^{-1}, respectively) and the lowest $T_{1/2}$ among treatments (14 and 17 days). The predominance of leaves and flowers in their residues, rich in labile compounds and nutrients, likely favored their rapid decomposition process (Cotrufo et al., 2015; Khatounian, 2001; Otte et al., 2019). The evolution of the C/N ratio in Fabaceae species supports this hypothesis (Figure 2D), as the lower proportion of recalcitrant organs, such as lignified stems with high polyphenols content, resulted in lower C/N ratio values over time compared to grasses.

This result is consistent with the findings of Calonego et al. (2012), who also reported that the C/N ratios of the legume CC *Dolichos lablab* L. were lower than those observed for Poaceae species over a 135-day evaluation period. Therefore, the observed increase in the C/N ratio after 30 days (Figure 2D), for all treatments, could be associated with the decomposition of recalcitrant compounds, such as cellulose and hemicellulose, following the final degradation process of leaves and flowers (as evidenced by visual assessments). Similar findings have been reported by Weiler et al. (2022), suggesting that the breakdown of cellulose intensifies after the decomposition of labile compounds. Against this background, the variations in C/N ratios among CC over time could also be attributed to the higher concentrations of polyphenols and lignin in Poaceae residues compared to those of Fabaceae species (Table 1)

Additionally, despite presenting similar C/N ratios, Congo grass and pearl millet exhibited markedly different decomposition dynamics. Congo grass decomposed more rapidly, with a higher K value (0.0320 day^{-1}) and shorter half-life ($T_{1/2}$ = 21 days) than pearl millet (K = 0.0242 day^{-1}; $T_{1/2}$ = 28 days). This divergence suggests that other biochemical traits, such as lignin content, may have exerted a decisive influence in regulating decomposition rates. These results reinforce that the C/N ratio alone is not a sufficient predictor of residue degradation, aligning with previous findings that emphasize the influence of structural compounds like lignin and polyphenols (Singh et al., 2020; Thapa et al., 2022; Weiler et al., 2022).

Interestingly, these both species exhibited similar PRQI values (Table 5), which, according to Tian, Brussaard, & Kang (1995), would imply comparable rates of biomass decomposition and N release. However, the present findings contradict this expectation, as pearl millet and Congo grass displayed distinct values for both K and $N_{1/2}$, indicating clear differences in DM and N release dynamics. These results suggest that PRQI alone may not fully capture the complexity of residue decomposition, particularly when factors such as N forms or tissue compartmentalization play a significant role in regulating mineralization processes.

Furthermore, our findings on biomass decomposition rates differ from those reported by Costa et al. (2016), who observed slower decomposition of *Urochloa* spp. compared to pearl millet. These discrepancies could be derived from environmental conditions (air temperature and humidity), differences in the phenological stage at termination, or methodological factors related to the litter bag technique. In this sense, Saadat et al. (2025) highlight that variations in litter bag preparation (residue particle size, drying methods and amount of residue) can significantly affect biomass decomposition and N release, influencing microbial activity and the comparability of results across studies (Keuskamp et al., 2013).

The maize crop, in turn, exhibited the lowest K value (0.00179 day^{-1}) and the highest $T_{1/2}$ (39 days). This response can be attributed to the high initial C/N ratio and lignin content (Table 1), as well as the greater proportion of recalcitrant fractions compared to labile ones (Chen et al., 2009). Moreover, it is noteworthy that the $T_{1/2}$ and $N_{1/2}$ values observed in this study were at least twice as low as those typically reported in rainfed conditions (Hahn et al., 2024; Moreira et al., 2009; Pacheco et al., 2017). In contrast, our results were more similar to those found by Torres et al. (2021) under irrigated conditions, suggesting that favorable climatic conditions, particularly accumulated rainfall, played a crucial role in enhancing microbial activity and thereby accelerating residue decomposition and N release.

In this sense, the high relative humidity (RH) and frequent rainfall events observed during the first month of evaluation (November 2024) likely contributed to the accelerated breakdown of more labile residues (Figure 2). These findings align with Thapa et al. (2022), who highlighted precipitation and RH as key drivers of residue decomposition. Additionally, the use of fresh (non-dried) residues in the litter bags could also have contributed to the shorter half-life values observed in this study, as reported by Saadat et al. (2025).

3.2 Cover crops N release

The remaining N trend followed a similar pattern to DM loss, with significant differences between treatments ($p < 0.01$) (Table 4; Figure 2B). This effect was supported by the η^2 values, which also indicated a strong influence of species-specific residue quantity and quality on N retention during the early stages ($\eta^2 = 0.50$ at 15 days), with a progressive reduction over time ($\eta^2 = 0.30$ at 90 days). In this manner, previous studies indicate that N release is directly related to plant decomposition, as most nutrients are concentrated in leaf tissues for structural and storage functions (Doneda et al., 2012; Varela et al., 2017).

Table 4: Mean values (n = 4) of remaining nitrogen in cover crop plant residues at each sampling period, reflecting the dynamics of nitrogen release during decomposition. Piracicaba-SP, Brazil.

Species	Time (days)				
	0	15	30	60	90
	Percentage of Remaining Nitrogen (% - g kg^{-1})				
Zea mays	100	63 a	52 a	39 a	32 a
Pennisetum glaucum	100	55 ab	42 b	32 ab	27 ab
Urochloa ruziziensis	100	51 ab	39 bc	27 b	23 b
Crotalaria juncea	100	43 c	31 bc	25 bc	16 bc
Canavalia ensiformis	100	38 d	28 c	20 c	12 c
CV (%)	0.0	18.31	18.27	12.90	25.96
p-value	--	< 0.001	< 0.001	< 0.001	< 0.001
$\eta2$	--	0.50**	0.45**	0.45**	0.40**
	Remaining Nitrogen (kg ha^{-1})				
Pennisetum glaucum	216.14	50.47 a	28.22 a	17.70 a	11.41 a
Crotalaria juncea	244.80	36.81 ab	20.86 ab	12.46 ab	4.94 b
Urochloa ruziziensis	138.18	34.88 ab	22.20 ab	12.03 ab	7.66 ab
Zea mays	62.12	20.23 bc	12.80 bc	8.03 bc	5.03 b
Canavalia ensiformis	103.30	17.63 c	9.72 c	4.72 c	1.86 c
CV (%)	36.41	35.33	33.74	35.79	32.84
p-value	--	< 0.001	< 0.001	< 0.001	< 0.001
$\eta2$	--	0.45**	0.40**	0.35**	0.30**

Means followed by the same letter in the same column do not differ significantly according to Tukey's test at the 5% significance level within the same evaluation period. CV (%): coefficient of variation. *p*-value: probability associated with the F-test from analysis of variance (ANOVA). η^2: effect size, indicating the proportion of variance explained by the quantity and quality of the summer cover crops plant residues (treatments) at each sampling time; **values > 0.14 represent a large treatment effect.

Nevertheless, the NAR from pearl millet (206 kg ha^{-1}) after 90 days was higher than that of jack bean (101 kg ha^{-1}) and comparable to sunn hemp (Table 5). This result contrasts with previous studies reporting that Poaceae species generally release less N than legumes (Canalli et al., 2020; 2012; Adetunji et al., 2020). Thus, rather than botanical classification, our results suggests that N release dynamics appear to be more strongly influenced by biomass production and the phenological stage at termination (Khatounian, 2001; Adetunji et al., 2020). Supporting this interpretation, Singh et al. (2020) observed similar NAR patterns, attributing the rapid N release within two weeks of termination to elevated air temperatures and humidity during the early decomposition phase, as well as to the early termination management of CC, which preserved a higher proportion of labile compounds in plant tissues.

Thereafter, clear differences were observed among CC species in terms of K_N and $N_{1/2}$ (Table 4). Jack bean and Sunn hemp exhibited the fastest N release, with K_N values of 0.0435 and 0.0338 day^{-1} and $N_{1/2}$ of 16 and 20 days, respectively, likely due to their high content of labile compounds and low initial C/N ratios. Congo grass exhibited intermediate values (K_N = 0.0242 day^{-1}; $N_{1/2}$ = 28 days), while pearl millet presented a slightly lower K_N (0.0198 day^{-1}) and higher $N_{1/2}$ (35 days), probably reflecting its higher lignin content (Table 1). Thus, maize exhibited the slowest N release among treatments, with the lowest K_N (0.0149 day^{-1}) and the highest $N_{1/2}$ (46 days), which can be attributed to the predominance of lignified stems and its higher initial C/N ratio. These differences are consistent with Weiler et al. (2019), who reported that higher proportions of recalcitrant compounds delay N mineralization, whereas residues rich in soluble and easily degradable fractions promote faster nutrient release (Table 1).

On the other hand, our findings contrast with those of Nascente et al. (2014), who reported significantly lower $N_{1/2}$ values for pearl millet compared to Congo grass and observed more marked differences in both $T_{1/2}$ and $N_{1/2}$ among CC. Nonetheless, our results are consistent with the well-established hypothesis that tropical legumes tend to release N more rapidly due to their lower C/N ratios and lignin content, whereas tropical grasses retain more biomass and thus provide more persistent soil cover (Hahn et al., 2024; Souza et al., 2025; Torres et al., 2021; Weiler et al., 2019). In addition, the overall performance of each species corroborated the expected balance between residue decomposition rate and mulch persistence.

3.3 Plant residue quality indices

The PRQI calculated using Equation (5) differed among the evaluated species, except for pearl millet and Congo grass, which showed similar values (Table 5). PRQI values ranged from 5.87 for maize to 16.44 for jack bean, supporting the assertion by Tian, Brussaard & Kang, (1995) that crop residues tend to have lower PRQI than agroforestry species. Considering biomass decomposition and N release, the plant residues of the analyzed species followed a descending PRQI order: jack bean > sunn hemp > pearl millet ≈ Congo grass > maize.

Table 5: Components and results of the indices that evaluate the quality of the plant residues from the summer cover crops at the end of 90 days. Piracicaba-SP, Brazil.

Species	NAR	RDM	NRI	RDMI	RBQI	PRQI
	----- (kg ha^{-1}) ----					
Pennisetum glaucum	206	2750	0.86	1.00	0.86	7.60
Urochloa ruziziensis	131	2344	0.55	0.85	0.47	7.57
Crotalaria juncea	240	1094	1.00	0.40	0.40	13.37
Zea mays	57	1250	0.24	0.45	0.11	5.87
Canavalia ensiformis	101	406	0.42	0.15	0.06	16.44
Ideal Cover crop	240	2750	1.00	1.00	1.00	---

NAR: Nitrogen accumulated release; RDM: Remaining dry matter; NIR: Nitrogen release index; RDMI: Remaining dry mass index; RBQI: Residual biomass quality index; PRQI: Plant residue quality index.

These results suggests that biomass decomposition may be sufficiently explained by the chemical composition of CC residues, as supported by previous studies (Gama-Rodrigues et al., 2007; Pacheco et al., 2017; Thapa et al., 2022; Weiler et al., 2022). Furthermore, the PRQI values obtained in this research showed a direct and significant ($p < 0.01$) correlation with the parameters K and K_N, a result also observed by Tian, Brussaard & Kang (1995) when evaluating plant residues from other five different species (Figure 3). However, these findings contrast with Mandro (2024), who found no significant differences in PRQI values among summer CC, likely due to the exclusion of polyphenol concentrations from the index calculation.

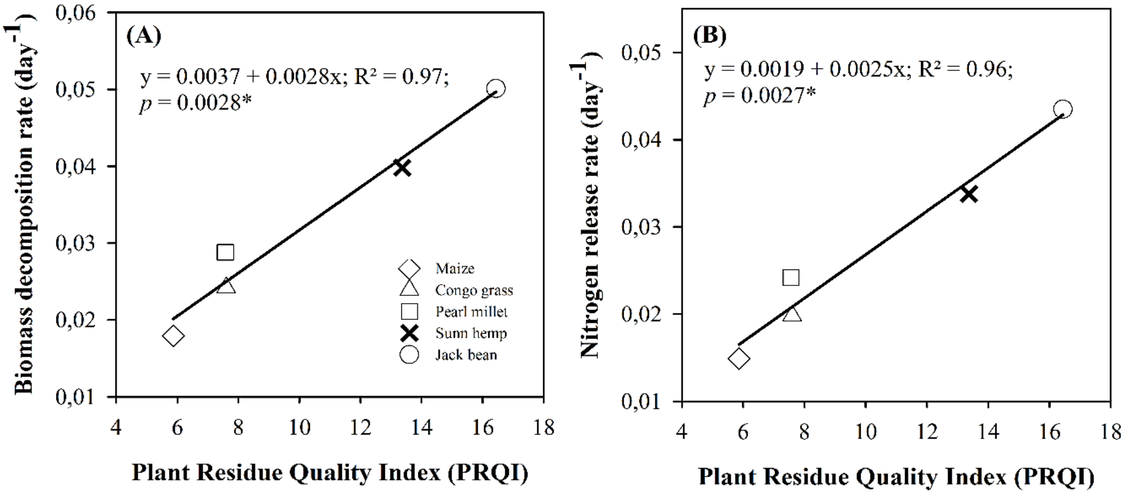

Figure 3: Linear regression analysis between the Plant Residue Quality Index (PRQI) and (A) biomass decomposition rate (K) and (B) nitrogen release rate (K_N) in residues of the evaluated summer cover crops. (*) indicates statistical significance of the linear regression analysis at the 1% level ($p < 0.01$).

Nonetheless, further research on plant residue from various CC and diverse climatic conditions are necessary to validate the applicability of PRQI, considering different agronomic factors. For instance, Tian, Brussaard & Kang (1995) observed a correlation between PRQI and key variables such as soil temperature, soil moisture levels, microbial diversity, and the yield of maize grown in succession, critical aspects that were not the objective of this study.

From this perspective, PRQI stands out as a potential predictive tool for assessing the response of CC residues in crop rotation systems. Its direct and significant correlation with the parameters K and K_N allows for an estimation of a species' decomposition rate and nutrient cycling potential even before sowing. This predictive capacity enables informed decision-making regarding species selection to align with specific agricultural objectives. For instance, in no-tillage systems, species with low PRQI values can enhance soil structure and moisture retention, whereas high PRQI species can rapidly supply N to subsequent crops, reducing fertilizer dependency (Souza et al., 2025; São Miguel et al., 2018; Tittonell & Giller, 2013).

Meanwhile, the RBQI represents a theoretical model based on the RDMI and NRI in comparison to an ideal species (Cassol et al., 2023). In this regard, sunn hemp and pearl millet were identified as the ideal CC for N release (240 kg ha^{-1}) and continuous soil cover (2750 kg ha^{-1}), respectively. Considering the balance between maximum NAR and the highest RDM production, the plant residues of the evaluated species followed the descending RBQI order: jack bean > maize > sunn hemp > Congo grass > pearl millet (Figure 4).

In this study, pearl millet exhibited the highest RBQI (0.86), indicating an optimal balance between soil cover maintenance and N release. Congo grass (0.55) and sunn hemp (0.40) showed intermediate performance, with Congo grass standing out for its favorable combination of residue persistence and N availability. Conversely, maize (0.11) and jack bean (0.06) presented the lowest RBQI values, reflecting either limited N release or rapid biomass decomposition, patterns likely driven by differences in chemical composition and C/N ratios.

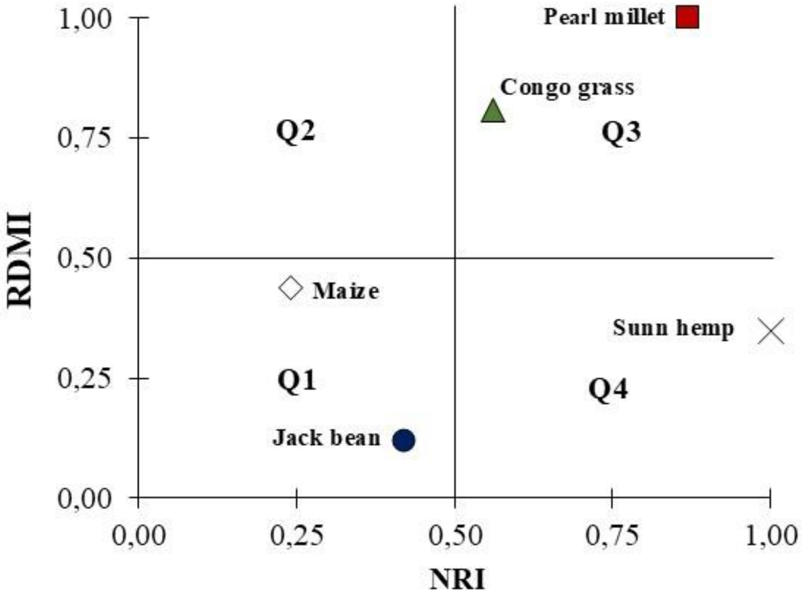

Figure 4: Points of intersection of the Remaining Dry Matter Index (RDMI) and Nitrogen Release Index (NRI) of the evaluated summer cover crops species. Piracicaba-SP, Brazil.

The superior performance of tropical forage species, particularly pearl millet and Congo grass can be attributed to their higher DM production and greater concentrations of lignin and polyphenols (Table 1), which contributed to longer residue persistence and a more gradual N release over the 90-day evaluation period. These findings align with previous studies emphasizing the role of forage grasses in improving efficiency of nutrient use, reducing N yield gaps, and enhancing soil protection in tropical cropping systems (Baptistella et al., 2020; Batista et al., 2024; Souza et al., 2024). Additionally, the higher RBQI values observed for pearl millet and Congo grass corroborate the results reported by São Miguel et al. (2018) and Araújo et al. (2024), who highlighted the agronomic benefits of these species in tropical crop rotations, particularly their contributions to soil cover and nutrient cycling efficiency.

Thus, although both PRQI and RBQI aim to evaluate plant residue quality, they appear to serve distinct purposes and are grounded in different theoretical approaches. PRQI, based exclusively on the chemical composition of plant residues, is intended to estimate their potential for decomposition and nutrient release. RBQI, in turn, incorporates experimental data on N release and biomass persistence in relation to a reference standard. From this perspective, PRQI may be more applicable to preliminary assessments before field application, while RBQI seems more appropriate for retrospective analyses grounded in empirical data.

Ultimately, the adoption of PRQI and RBQI presents a promising strategy for selecting CC species according to specific agronomic goals, with potential benefits for soil conservation and nutrient management in tropical systems (Souza et al., 2025; Rigon, Franzluebbers & Calonego, 2020). Despite that, the present study was limited to a single cropping season, one geographical location, and focused solely on CC species, without including field measurements of soil nutrient dynamics or cash crop responses. Additionally, the use of the litter bag method may not fully represent natural decomposition processes due to microenvironmental alterations. Therefore, future research should evaluate these indices under a wider range of edaphoclimatic conditions, across multiple years, and integrate direct assessments of soil fertility and cash crop productivity to improve the robustness and practical applicability of our findings.

4. CONCLUSIONS

(1) CC from the Fabaceae family exhibited higher K and K_N values, along with lower $T_{1/2}$ and $N_{1/2}$. Among the Poaceae species, *Pennisetum glaucum* exhibited higher NAR (206 kg ha-1) and RDM (2.75 Mg ha^{-1}) values, highlighting its potential for crop rotation in no-till systems in tropical environments;

(2) The high relative humidity, accumulated rainfall, and early species termination probably accelerated biomass decomposition and NAR within the first 15 days of the experimental period, as reflected in the low $T_{1/2}$ and $N_{1/2}$ values observed across all treatments;

(3) The plant residue quality indices revealed differences among the evaluated summer CC, assisting in classifying their potential for crop rotation systems. PRQI showed a significant and direct correlation with K and K_N, while RBQI highlighted the ability of *Pennisetum glaucum* and *Urochloa ruziziensis* to provide a better balance of RDM and NAR. These findings can support the selection of CC in tropical rotations to improve both N cycling and soil

conservation. Continued studies in diverse environments and over multiple cropping sites are recommended for further validation of these indices.

5. AUTHORS CONTRIBUTION

Conceptual idea: Dias, V.O.; Favarin, J.L.; Khatounian, C.A.; Methodology design: Dias, V.O.; Favarin, J.L.; Souza, M.E.A.; Santana, D.M.; Ribas, G.G.; Data collection: Dias, V.O.; Souza, M.E.A.; Santana, D.M.; Data analysis and interpretation: Dias, V.O.; Souza, M.E.A.; Khatounian, C.A.; Piero, J.A.R.; Writing and editing: Dias, V.O.; Favarin, J.L.; Khatounian, C.A.; Piero, J.A.R.; Ribas, G.G.

6. ACKNOWLEDGEMENTS

The authors thank the Unified Scholarship Program of the University of São Paulo (PUB-USP) for granting a Scientific Initiation scholarship to the first author (code 4422.2024), the Graduate Program in Crop Science at ESALQ/USP, and the Fundação de Estudos Agrários “Luiz de Queiroz” (FEALQ) for contributing to the article processing charge. The authors also express their sincere gratitude to all editors and reviewers for their time and careful evaluation, which greatly contributed to improving the quality and clarity of this work.

7. CONFLICT OF INTEREST

The authors declare no competing financial or personal interests that could have influenced the work reported in this manuscript.

8. DATA AVAILABILITY

The data that support the findings of this study are not publicly available but can be obtained from the corresponding author upon request (victordeoliveiradias@usp.br).

9. REFERENCES

Adetunji, A. T., Ncube, B., Mulidzi, R., & Lewu, F. B. (2020). Management impact and benefit of cover crops on soil quality: A review. *Soil and Tillage Research*, 204(1):1-11.

Alonso-Ayuso, M., Gabriel, J. L., Hontoria, C., Ibáñez, M. Á., & Quemada, M. (2020). The cover crop termination choice to designing sustainable cropping systems. *European Journal of Agronomy*, 114:126000.

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(6):711-728.

Anderson, J. N., & Ingram, J. S. I. (1996). *Tropical soil biology and fertility: A handbook of methods* (2nd ed.). Wallingford (UK): CAB International.

Araújo, F. C., Nascente, A. S., Filippi, M. C. C., & Silva, M. A. (2024). Mixes of cover crops and Trichoderma asperellum for enhancing soybean crop yield and sustainability. *Pesquisa Agropecuária Tropical*, 54(1):1-10.

Baptistella, J. L. C., Andrade, S. A. L., Favarin, J. L., & Mazzafera, P. (2020). Urochloa in tropical agroecosystems. *Frontiers in Sustainable Food Systems*, 4(1):1-17.

Batista, K., Giacomini, A. A., Gerdes, L., Mattos, W. T., & Otsuk, I. P. (2024). Potential interaction of soybean-grass intercropping with residual nitrogen for a no-tillage system implementation. *Acta Scientiarum. Agronomy*, 46(1):1-12.

Calonego, J. C., Gil, F. C., Rocco, V. F., & dos Santos, E. A. (2012). Persistência e liberação de nutrientes da palha de milho, braquiária e labe-labe. *Bioscience Journal*, 28(5):1-10.

Campos, B. H. C., Amado, T. J. C., Bayer, C., da Silveira Nicoloso, R., & Fiorin, J. E. (2011). Carbon stock and its compartments in a subtropical Oxisol under long-term tillage and crop rotation systems. *Revista Brasileira de Ciência do Solo*, 35(3):1-13.

Canalli, L. B., Bruschi, J., Barbosa, G. F., & Cardoso, A. P. (2020). Plant residue decomposition and soil carbon dynamics in integrated systems. *Soil and Tillage Research*, 204(1):1-11.

Cassol, C., Conceição, P. C., Amadori, C., Haskel, M. K., de Freitas, L. A., & Tomazoni, A. R. (2023). Residual biomass quality index: A tool for conservation agriculture. *Revista Brasileira de Ciência do Solo*, 47(1):1-18.

Chang, P., Secco, D., Marins, A. C., Rizzi, R. L., Bassegio, D., & Savioli, M. R. (2023). Modeling nutrient losses in an Oxisol under different management systems and rainfall events. *Bragantia*, 83(1):1-14.

Chen, H., Fan, M., Billen, N., Stahr, K., & Kuzyakov, Y. (2009). Effect of land use types on decomposition of 14C-labelled maize residue (Zea mays L.). *European Journal of Soil Biology*, 45(2):123-130.

Costa, C. H. M.; Crusciol, A. C.; Soratto, R. P.; Neto, J. F. Phytomass decomposition and nutrients release from pearl millet, guinea grass and palisade grass. *Bioscience Journal*, 32(5):1284-1294, 2016.

Cotrufo, M. F., Soong, J. L., Horton, A. J., Campbell, E. E., Haddix, M. L., Wall, D. H., & Parton, W. J. (2015). Formation of soil organic matter via biochemical and physical pathways of litter mass loss. *Nature Geoscience*, 8(10):776-779.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale, New Jersey, United States: Lawrence Erlbaum Associates, 567p.

Doneda, A., Aita, C., Giacomini, S. J., Miola, E. C. C., Giacomini, D. A., Schirmann, J., & Gonzatto, R. (2012). Fitomassa e decomposição de resíduos de plantas de cobertura puras e consorciadas. *Revista Brasileira de Ciência do Solo*, 26(6):1-10.

Gama-Rodrigues, C. A., Forestieri, D. G., da Gama-Rodrigues, E., & Cruz de Brito, E. (2007). Decomposição e liberação de nutrientes de resíduos culturais de plantas de cobertura em Argissolo Vermelho-Amarelo na região noroeste fluminense (RJ). *Revista Brasileira de Ciência do Solo*, 31(6):1421-1428.

Hahn, L., Wamser, A. F., Wolschick, N. H., Grando, D. L., Siqueira, G. N., & Brunetto, G. (2024). Garlic yield after decomposition and nutrient release of cover crops under no-tillage and conventional tillage. *Revista Brasileira de Ciência do Solo*, 48(1):1-15.

Keene, C. L., Curran, W. S., Wallace, J. M., Ryan, M. R., Mirsky, S. B., VanGessel, M. J., & Barbercheck, M. E. (2017). Cover crop termination timing is critical in organic rotational no-till systems. *Agronomy Journal*, 109(1):272-282.

Keuskamp, J. A., Dingemans, B. J., Lehtinen, T., Sarneel, J. M., & Hefting, M. M. (2013). Tea Bag Index: A novel approach to collect uniform decomposition data across ecosystems. *Methods in Ecology and Evolution*, 4(11):1070-1075.

Kim, D. H., Wade, T., Brym, Z., Ogisma, L., Bhattarai, R., Bai, X., Bhadha, J., & Her, Y. (2025). Assessing the agricultural, environmental, and economic effects of crop diversity management: A comprehensive review on crop rotation and cover crop practices. *Journal of Environmental Management*, 387:125833.

Khatounian, C. A. (2001). *A reconstrução ecológica da agricultura*. Londrina (PR): IAPAR.

Lima-Filho, O. F. et al. (2023). Adubação verde e plantas de cobertura no Brasil: fundamentos e prática. 2. ed. rev. atual. Brasília, DF: Embrapa, 586p.

Lovato, T., Mielniczuk, J., Bayer, C., & Vezzani, F. (2004). Adição de carbono e nitrogênio e sua relação com os estoques no solo e com o rendimento do milho em sistemas de manejo. *Revista Brasileira de Ciência do Solo*, 28(1):175-187.

Machado, P. L. O. A., & Silva, C. A. (2001). Soil management under no-tillage systems in the tropics with special reference to Brazil. *Nutrient Cycling in Agroecosystems*, 61(1):119-130.

Mandro, M. A. E. (2024). Quantidade e qualidade da biomassa de plantas de cobertura do solo e seus efeitos na soja sob semeação direta. 2024. 53f. Dissertação (Mestrado em Fitotecnia), Escola Superior de Agricultura “Luiz de Queiroz”, Universidade de São Paulo, Piracicaba.

Mangaravite, J. C. S., Passos, R. R., Andrade, F. V., da Silva, V. M., Marin, E. B., & de Sá Mendonça, E. (2023). Decomposition and release of nutrients from species of tropical green manure. *Revista Ceres*, 70(3):114-124.

McMaster, G. S., & Wilhelm, W. W. (1997). Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology*, 87(1):291-300.

Medina, C. S. V. J., Aita, C., Bordin, I., Preti, E., Zaccheo, P. V. C., de Aguiar, R. S., & Urquiaga, S. (2013). Aporte de matéria seca por raízes e parte aérea de plantas de cobertura de verão. *Semina: Ciências Agrárias*, 34(2):675-682.

Moreira, A., Souza, L. L. P., Castro, P. A. C. A., & Júnior, R. G. (2009). Composição química de plantas de cobertura e decomposição de resíduos vegetais. *Boletim de Pesquisa e Desenvolvimento*, 258(1):1-14.

Nascente, A. S.; Crusciol, C. A. C.; Stone, L. F. Straw degradation and nitrogen release from cover crops under no-tillage. *Revista Caatinga*, 27(2):166-175, 2014.

Otte, B., Mirsky, S., Schomberg, H., Davis, B., & Tully, K. (2019). Effect of cover crop termination timing on pools and fluxes of inorganic nitrogen in no-till corn. *Agronomy Journal*, 111(6):2832-2842.

Pacheco, L. P., Monteiro, M. M. S., Petter, F. A., Nóbrega, J. C. A., & dos Santos, A. S. (2017). Produção de fitomassa e ciclagem de nutrientes por plantas de cobertura no Cerrado Piauiense. *Revista Caatinga*, 30(1):13-23.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G., & Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems & Environment*, 83(1-2):27-42.

Possamai, E. J., Conceição, P. C., Amadori, C., Bartz, M. L., Ralisch, R., Vicensi, M., & Marx, E. F. (2022). Adoption of the no-tillage system in Paraná State: A (re)view. *Revista Brasileira de Ciência do Solo*, 46(1):1-24.

Raij, B. van, Andrade, J. C., Cantarella, H., & Quaggio, J. A. (2001). *Análise química para avaliação da fertilidade de solos tropicais*. Instituto Agronômico, Campinas.

Rigon, J. P. G., Franzluebbers, A. J., & Calonego, J. C. (2020). Soil aggregation and potential carbon and nitrogen mineralization with cover crops under tropical no till. *Journal of Soil and Water Conservation*, 75(5):601-609.

Saadat, D.; Hashemi, M.; Herbert, S.; Siller, A. (2025). Contribution of roots and shoots of three summer cover crops to soil C and N cycling post-termination. Agronomy, 15(6):1467.

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo Filho, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). *Brazilian Soil Classification System* (5th ed.). Brasília (DF): Embrapa. Available at: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1094001>. Accessed: 24 jun. 2025.

São Miguel, A. S., Pacheco, L. P., Carvalho, Í. C., Souza, E. D., Feitosa, P. B., & Petter, F. A. (2018). Phytomass and nutrient release in soybean cultivation systems under no-tillage. *Pesquisa Agropecuária Brasileira*, 53(10):1119-1131.

Singh, G., Dhakal, M., Yang, L., Kaur, G., Williard, K. W. J., Schoonover, J. E., & Sadeghpour, A. (2020). Decomposition and nitrogen release of cover crops in reduced- and no-tillage systems. *Agronomy Journal*, 112(5):3605-3618.

Sodré-Filho, J., Carvalho, A. M., Marchão, R. L., & Carmona, R. (2024). Decomposition of sorghum, grass, and sorghum intercropped with grass and soybean performance in integrated systems in the Cerrado. *Scientia Agricola*, 81(1):1-8.

Souza, V. S., Canisares, L. P., Schiebelbein, B. E., Castro Santos, D., Menillo, R. B., Pinheiro Junior, C. R., & Cherubin, M. R. (2025). Cover crops enhance soil health, crop yield and resilience of tropical agroecosystem. *Field Crops Research*, 322(1):1-12.

Souza, L. F. N., Ciampitti, I. A., Fernandez, J. A., Favarin, J. L., & Oliveira, S. M. (2024). Maize-Brachiaria grass intercropping: A meta-analysis of major productivity drivers in Brazil. *Field Crops Research*, 306(1):1-9.

Tedesco, M. J., Gianello, C., Bissani, C. A., Bohnen, H., & Volkweiss, S. J. (1995). *Análises de solo, plantas e outros materiais* (2nd ed.). Porto Alegre (BR): Universidade Federal do Rio Grande do Sul.

Thapa, R., Tully, K. L., Reberg-Horton, C., Cabrera, M., Davis, B. W., Fleisher, D., et al. (2022). Cover crop residue decomposition in no-till cropping systems: Insights from multi-state on-farm litter bag studies. *Agriculture, Ecosystems & Environment*, 326:107823.

Tian, G., Brussaard, L., & Kang, B. T. (1995). An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics. *Applied Soil Ecology*, 2(1):25-32.

Torres, J. L. R., Gomes, F. R. C., Barreto, A. C., Orioli Junior, V., França, G. D., & Lemes, E. M. (2021). Nutrient cycling of different plant residues and fertilizer doses in broccoli cultivation. *Horticultura Brasileira*, 39(1):11-19.

Telles, T. S., Righetto, A. J., Lourenço, M. A. P., & Barbosa, G. M. C. (2020). No-tillage system participatory quality index. *Revista Brasileira de Engenharia Agrícola e Ambiental*, 24(2):128-133.

Tittonell, P., & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research*, 143(1):76-90.

Van Soest, P. J., Robertson, J. B., & Lewis, B. A. (1991). Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *Journal of Dairy Science*, 74(10):3583-3597.

Varela, M. F., Barraco, M., Gili, A., Taboada, M. A., & Rubio, G. (2017). Biomass decomposition and phosphorus release from residues of cover crops under no-tillage. *Agronomy Journal*, 109(1):317-326.

Weiler, D. A., Bastos, L. M., Schirmann, J., Aita, C., & Giacomini, S. J. (2022). Changes in chemical composition of cover crops residue during decomposition. *Ciência Rural*, 52(4):1-4.

Weiler, D. A., Giacomini, S. J., Aita, C., Schmatz, R., Pilecco, G. E., Chaves, B., et al. (2019). Summer cover crops shoot decomposition and nitrogen release in a no-tilled sandy soil. *Revista Brasileira de Ciência do Solo*, 43(1):1-12.

Thomas, R. J., & Asakawa, N. M. (1993). Decomposition of leaf litter from tropical forage grasses and legumes. *Soil Biology and Biochemistry*, 25(10):1351-1361.

Este preprint foi submetido sob as seguintes condições:

- Os autores declaram que estão cientes que são os únicos responsáveis pelo conteúdo do preprint e que o depósito no SciELO Preprints não significa nenhum compromisso de parte do SciELO, exceto sua preservação e disseminação.

- Os autores declaram que os necessários Termos de Consentimento Livre e Esclarecido de participantes ou pacientes na pesquisa foram obtidos e estão descritos no manuscrito, quando aplicável.

- Os autores declaram que a elaboração do manuscrito seguiu as normas éticas de comunicação científica.

- Os autores declaram que os dados, aplicativos e outros conteúdos subjacentes ao manuscrito estão referenciados.

- O manuscrito depositado está no formato PDF.

- Os autores declaram que a pesquisa que deu origem ao manuscrito seguiu as boas práticas éticas e que as necessárias aprovações de comitês de ética de pesquisa, quando aplicável, estão descritas no manuscrito.

- Os autores declaram que uma vez que um manuscrito é postado no servidor SciELO Preprints, o mesmo só poderá ser retirado mediante pedido à Secretaria Editorial do SciELO Preprints, que afixará um aviso de retratação no seu lugar.

- Os autores concordam que o manuscrito aprovado será disponibilizado sob licença Creative Commons CC-BY.

- O autor submissor declara que as contribuições de todos os autores e declaração de conflito de interesses estão incluídas de maneira explícita e em seções específicas do manuscrito.

- Os autores declaram que o manuscrito não foi depositado e/ou disponibilizado previamente em outro servidor de preprints ou publicado em um periódico.

- Caso o manuscrito esteja em processo de avaliação ou sendo preparado para publicação mas ainda não publicado por um periódico, os autores declaram que receberam autorização do periódico para realizar este depósito.

- O autor submissor declara que todos os autores do manuscrito concordam com a submissão ao SciELO Preprints.