From Leaf to Soil: Exploring the Dynamics of Leaf Litter Production and Decomposition in a Sal Forest Ecosystems in Jharkhand, India

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Abstract

Understanding the complex processes of leaf litter production and decomposition is essential for understanding the nutrient cycle and ecosystem functioning in various terrestrial settings. The dynamics of leaf litter in Sal (*Shorea robusta*) forest ecosystems are investigated in this work. With comprehensive field sampling, quantification of the changes in leaf litter and pinpointing the underlying causes of these variances. This year-long study delved into the dynamics of litter in the Sal Forest across seven distinct locations. Results aligned with prior findings, emphasizing the role of Sal tree phenology and local climate, particularly temperature, in litter production dynamics. Sample point 6, inside a dense forest, stood out with abundant vegetation and diverse species, exhibiting optimal litter decomposition, nutrient accumulation, and utilization due to favorable temperature and humidity with a decay constant of 0.5358. May, June, and July fostered the highest decomposition, with a total mass loss of ~ 84.68%. Principle composite correlation value of soil factors such as pH (0.812), water holding capacity (0.924), moisture content (0.944), soil organic carbon (0.772), soil carbon (0.893), soil nitrogen (0.857), soil phosphorous (0.847), and soil potassium (0.726) and humidity (0.836) suggests that these factors significantly influence decomposition. The research underscores the intricate nature of litter decomposition, shaped by Sal tree phenology, climate, vegetation cover, and soil properties, collectively driving the Sal Forest ecosystem's ecological processes. This study provides a thorough picture of the transit of leaf litter from the forest canopy to the forest floor to comprehend the intricate links between leaf litter production and soil health in Sal Forest ecosystems.

Introduction

Nature's cycles are like symphonies of harmony, and the complex interplay between leaf litter production and breakdown forms the core of this symphony. The towering trees' leaves begin a stunning transition as they fall gracefully to the ground, nourishing the soil and maintaining a complex web of life. Sal forests (*Shorea robusta*) are extensively dispersed throughout tropical India, accounting for around 13.3% of the country's total forest area (Upreti & Nayaka, 2005). Sal is a major tree species in India's tropical moist, and dry deciduous forests (Champion & Seth, 1968). Jharkhand, is known as the land of forest, has a vast Sal Forest region in Eastern India. This area is densely forested and covers the state's reported forest area of 23,606 $km^{2,}$ or 29.62% of the state's geographical area (Kumar et al., 2022). These reserved woods account for 18.59% of the total forest area, whereas protected forests account for 81.29% and unclassified forests account for 0.15%. The forest provides people with livelihoods through wood and non-timber forest products and is a significant habitat for various species. Sal woodland is under threat from a variety of human factors, which are exacerbated by climate change. The optimal growth conditions for Sal forests include moist, slightly acidic sandy to clayey soils. These forests naturally regenerate through seed dispersal. However, human activities such as burning, grazing, and deforestation have negatively impacted this regeneration process, reducing success under significant anthropogenic interference (Timilsina et al., 2007).

A forest is an open system with chemical components flowing in and out and inside it (Fig. 1). In numerous ways, the forest floor is an essential component of the forest ecosystem. Litter from the standing crop contributes significantly to the floor. Yang et al. (2022) and Rodrigues et al. (2020) discuss the availability and sufficiency of nutrients supplied to soil by the degradation of forest floor residues. Plant litter is the major source of energy and nutrients in stream ecosystems, and its decomposition is vital for ecosystem nutrient cycling and functioning (Yue et al., 2022). The decomposition of dead organic matter feeds the major terrestrial global CO_2 flux to the atmosphere (Joly et al.,2023). It promotes tree development and accelerates the biological activity of the organism in the soil. Furthermore, it supports the physical development of the soil as well as increased crop yield. Litter helps to retain soil moisture by chilling the ground surface and trapping moisture in decomposing organic materials. The flora and fauna that work to decompose leaf litter also help with soil respiration. A degrading leaf biomass litter layer offers a constant energy source for macro- and micro-organisms. Litterfall restores more than half of a forest's net primary output to the soil (Feng et al., 2019). Litter decomposition is an important process in ecosystems because it contributes to the emission and storage of carbon (C), the release of nutrients, and the creation of humic compounds in the soil (Berg, 2000; Parton et al., 2007). Litter's chemical, biological, and physical properties change as it decomposes, and the relative role of variables affecting its decomposition may also alter.

According to reports, leaf litter decomposition occurs in three stages. (Berg & McClaugherty, 2014). The primary cause of mass loss is leaching during the initial stage of litter decomposition. The soluble and non-lignified components (cellulose and hemicellulose) are degraded in the second step (Heim & Frey, 2004). The breakdown of lignified tissues happens in the third stage of decomposition and is mostly regulated by litter chemistry (Zhou et al., 2015) (Fig. 2).

For *Shorea robusta*, maximum leaf-fall occurs from mid-February to mid-May (Pokhriyal et al.,1987; Singh et al., 1993a) observed in Indian Sal Forest along the tropics. Investigating the amount of litterfall and the pace at which it decomposes is still an essential component of forest ecology since it deals with a key energy and nutritional transfer conduit (Bray & Gorham, 1964). The habitat type most strongly influences the pattern of litterfall. The study's goal is to compare litter nutrient dynamics in Sal woodland. The study aims to (i) estimate monthly and seasonal production of litter, (ii) analyze the link of litter production with climatic factors, and (iii) assess litter decomposition and nutrient mineralization dynamics.

Material and methods

Study area

The area of interest for this study is located in Ranchi, Jharkhand, India (Fig. 3). It has a 187-hectare area and is situated at 23.4123°N and 85.4399°E close to the confluence of the rivers Jhumar and Swarnarekha. It is bordered by a lush Sal (*Shorea Robusta*) forest. This tree species belongs to the Dipterocarpaceae family, known as Sal, sakhn, or shala tree. This area comes under a humid subtropical climate type (Köppen Climate Classification: *Cwa*). Physiographically, this area is a plateau region named Chotanagpur Plateau. The soil in the research area is lateritic and iron-rich, able to retain nutrients; thus, it contains a good amount of organic carbon.

Figure No 3: Study area.

Collection and measurement of leaf litter samples

The monthly litter contributions were calculated based on the components that fell during the year. The experiment spanned an entire year, during which it was periodically assessed at two-month intervals, commencing in March 2022, and concluding in March 2023 (Fig. 4). The Normalized Difference Vegetation Index (NDVI) is a numerical tool employed in remote sensing and satellite image analysis to evaluate and quantify vegetation's vitality, density, and robustness within a designated area. To comprehensively assess vegetation health and density across the entire forested region, the forest area was segmented into seven discrete NDVI categories, and sampling plots (1m^2 area) were thoughtfully selected from each of these classes. This stratified approach ensures a well-rounded representation of diverse ecological conditions within the study area. Litterfall was assessed by collecting seven litter samples from each type of plot (Xu et al., 2000). Litter samples were sorted into leaf and non-leaf components, carefully cleaned with water, air-dried, and then oven-dried at 60°C overnight. After that, the samples were pulverized for chemical analysis to determine C, H, N, S, P, Mg, K, Ca, Mn, and Fe. This monthly contribution of litter was calculated using dry weight, contribution per month, and surface area.

Analysis of leaf litter decomposition rates

A direct method of the litter bag technique was adopted (Swift & Anderson, 1989). Litter was collected from 7 plots, dried, and crumpled into the small nylon mesh bags (10*10 cm). Approximately 15gm of litter in 6 litter bags were placed in each plot and were kept randomly on the undisturbed floor of all 7 plots. Three bags from each plantation were removed regularly at two-month intervals. Foreign particles were separated from the samples. These samples were dried, weighed, and then stored for chemical analyses. This data collection and processing procedure was repeated continuously. The information from Table 1 was utilized to compute various parameters.

Table 1
Parameter calculated with equation description and reference.

Parameter	Equation	Description	Reference
Turnover rate of litter (K_l)	$K_L = \frac{A}{A+F}$	A (g m^{-2}) is the annual increment of litter (i.e., annual litterfall) F (g m^{-2}) is the mean monthly litter (annual average across months)	Olson 1963; Dev & Yadava 2010
Decomposition constant (k)	$\frac{W_t}{W_0} = e^{-kt}$	W_0 and W_t are oven-dry litter's initial and remaining (at time t) weights. t is the elapsed time (year) k is the decay constant.	Olson 196
Residence time of leaf litter (R_t)	$R_t = \frac{1}{k}$	k is the decay constant	Waring & Schlesing 1985
Nutrient Use Efficiency (NUE)	$NUE = \frac{M}{N}$	M is mass litterfall (g m^2) N is the nutrient content of litterfall (g m^2).	Vitousek 1984
Nutrient Retranslocation Efficiency (NRE%)	$NRE\,(\%) = 100\left(\frac{A-B}{A}\right)$	A is the nutrient in green leaves. B is the nutrient in leaf litter	Finzi et al. 2001
Nutrient Accumulation Index (NAI)	$NAI = \frac{W_t \times X_t}{W_0 \times X_0}$	W_t the dry weight at the time t (g) X_t the nutrient concentration at time t (mg g^{-1}) Wo the initial dry weight (g) Xo is the initial nutrient concentration (mg g^{-1})	Harmon e al. 1986
Half-life period $t_{0.5}$	$t_{0.5} = \frac{0.693}{k}$	k is the decay constant.	Waring & schlesinge 1985
Mass loss (%)	$MASS\,LOSS = 100 * \frac{W_0 - W_t}{W_0}$	W_0 and W_t are oven-dry litter's initial and remaining (at time t) weights.	Olson 196

Analysis of Leaf nutrient

Seven samples of green leaves were chosen to determine the concentrations of C, H, N, S, P, Mg, K, Ca, Mn, and Fe. The ground leaf litter and green leaf samples were tri-acid digested with HNO_3:$HClO_4$:H_2SO_4 (10:4:1) and analysed for concentrations of Mg, K, Ca, Mn, and Fe using ICP-OES; P via Spectrophotometer. CHNS analyser was used to get C, N, H, and S content.

Characterization of Soil

A digital pH meter was used to measured soil pH. Soil texture was determined by the hydrometer method. Organic carbon was estimated using the Walkley and Black (1934) method. Nitrate and phosphate were calculated using APHA 2003 method using a spectrophotometer. The gravimetric method measured soil moisture content using IS 2720: II (1973). CHNS analyzer was used to estimate C, H, N, and S content. Mg, K, Ca, Mn, and Fe were calculated using a digested sample in Inductively coupled plasma optical emission spectroscopy (ICP-OEC). pH, moisture content, water holding capacity, Phosphate, Organic carbon, soil carbon, soil nitrogen, soil phosphorous, and soil potassium are calculated bi-monthly and considered for statistical analysis.

Statistics Analysis

Analyzing the link between litter production and soil conditions using statistical tools like Pearson correlation, Analysis of Variance (ANOVA), and Principal Component Analysis (PCA). Pearson correlation analysis is a statistical technique to assess the strength and direction of the linear relationship between two continuous variables. When applied to studying the link between litter production and soil conditions, the Pearson correlation helps uncover potential associations and dependencies between these factors (Li et al., 2022). ANOVA is a statistical method that divides observed aggregate variability within a data set into systematic components and random factors. Random factors do not statistically impact the supplied data set, but systematic factors do (Peterson, 2000). In regression research, an ANOVA test was employed to examine the impact of independent factors on the dependent variable (Yin et al., 2021). Whereas PCA might provide an understanding of how different soil property variables contribute to changes in litter output by establishing a relationship between litter production and parameters (Kreye et al., 2023). The goal of PCA is straightforward: decrease the number of variables in a data collection while retaining as much information as feasible. PCA reduces the complexity of multi-dimensional data while preserving trends and patterns.

Results

The pattern of litterfall

The rate of litter production exhibited pronounced variation spatially and temporally within the study area. Specifically, the months of January (239.62 gm/m^2), March (210.96 gm/m^2), and May (216.05 gm/m^2) demonstrated the highest accumulation of fallen litter, whereas July (239.62 gm/m^2) registered the lowest return of litter. The sample points litter production rate was 114.23 gm/m^2 to 131.55 gm/m^2. Sample point 2 (131.55 gm/m^2) emerged as a prominent contributor to the overall litter production (Fig. 5).

The turnover rate represents the proportion of litter that decomposes or is removed from the sample point over a specified period (Fig. 6). These turnover rates indicate the variability in litter decomposition and turnover across different sample points and months. The turnover rates varied noticeably between sample locations and months, pointing to diverse processes of litter breakdown. Sample points 4 and 5 had much greater turnover rates in May (11.70% and 11.85%, respectively), indicating the litter was quickly turning into organic matter. The turnover rate for sample point 6 was lower for the same month, at 5.58%. July's sample point 5 turnover rate was the lowest, at 2.88%, indicating a more gradual decomposition process. Contrarily, sample point 6 showed a comparatively higher turnover rate of 5.61% for May. As September approached, sample point 5 recorded the highest turnover rate at 6.34%, indicating an increased pace of litter decomposition. Similarly, in March, sample point 6 experienced the highest turnover rate of 25.83%, highlighting a significant transformation of litter. Notably, July to November consistently demonstrated the most favorable turnover rates, implying more efficient litter breakdown processes in these months.

Decomposition rates and nutrient return dynamic

The decomposition rate refers to the speed at which organic material breaks down and transforms into simpler compounds, contributing to nutrient cycling and ecosystem processes. In May, sample point 6 exhibited the most rapid decomposition rate at 20.37%, indicating a substantial conversion of litter into organic matter. Sample point 7 also displayed a notable decomposition rate of 16.94% this month. As July arrived, sample point 5 exhibited a decomposition rate of 15.72%, highlighting a significant transformation of litter material. Sample point 6 is closely followed with a decomposition rate of 11.61%. In September, sample point 6 maintained its position with the highest decomposition rate at 28.7%, reinforcing its role as a hotspot for litter transformation. Sample point 7 also exhibited a considerable decomposition rate of 30.8% during this period. In November, sample point 6 sustained a high decomposition rate of 11.61%, while sample point 7 showed a rate of 10.84%, suggesting ongoing decomposition processes. In January, sample points 6 and 7 had decomposition rates of 6.38% and 7.58%, respectively, reflecting a comparatively slower decomposition phase during this month. Lastly, in March, sample point 1 displayed the highest decomposition rate at 4.71%, while samples 2, 3, 4, and 5 displayed no measurable decomposition (Fig. 7).

The decomposition constant (k) represents the rate at which leaf litter breaks down over time, with higher values indicating faster decomposition (Table 2). Sample point 1, characterized by a decomposition constant (k) of 0.06, portrays a moderate pace of decay. This is substantiated by a high R-squared (R^2) value of 0.96, indicating a robust fit of the exponential decay model to the empirical data. The residence time of leaf litter (R_t) for this specific location is calculated to be 15.39 months, implying that 15.39 months are required for half of the initial leaf litter to undergo decomposition. Correspondingly, the half-life period ($t_{0.5}$) is determined to be 10.67 months, marking the time for the initial amount of litter to decrease by half.

Moving to sample point 2, the decomposition constant (k) escalates to 0.10, reflecting a swifter rate of disintegration compared to sample 1. The commendable R-squared (R^2) value of 0.95 reaffirms the accuracy of the exponential decay model. Here, the residence time of leaf litter (R_t) dwindles to 9.61 months, resulting in a half-life period ($t_{0.5}$) of 6.66 months. Sample point 3 reveals a decomposition constant (k) of 0.13, hinting at a more accelerated decay process. Although the R-squared (R^2) value stands at 0.94, indicating a sound model fit, leaf litter (R_t) residence time further contracts to 7.98 months. Consequently, the half-life period ($t_{0.5}$) is calculated at 5.53 months, underscoring the swift pace of change.

Sample points 4, 5, and 6 boast decomposition constants (k) spanning from 0.08 to 0.11, encapsulating a range of decomposition rates. The R-squared (R^2) values for these points all exceed 0.94, with a residence time of leaf litter (R_t) extending from 9.24 to 13.06 months, yielding half-life periods ($t_{0.5}$) oscillating between 6.40 and 9.05 months. Lastly, sample point 7 had a decomposition constant (k) of 0.07, indicating a gradual decay rate. The notable R-squared (R^2) value of 0.97 with a residence time of leaf litter (R_t) stretches to 13.85 months, yielding a half-life period ($t_{0.5}$) of 9.60 months.

Table 2
Leaf litter decay rate coefficient (k), half-life ($t_{0.5}$), and residence time for various sample points.

Sample plot	Decomposition constant (k)	$Y = ae^{-kt}$	Residence time of leaf litter (R_t)	Half-life period ($t_{0.5}$)
	$Month^{-1}$	R^2	Month	Month
Sample point 1	0.06	0.96	15.39	10.67
Sample point 2	0.10	0.95	9.61	6.66
Sample point 3	0.13	0.94	7.98	5.53
Sample point 4	0.11	0.96	9.24	6.40
Sample point 5	0.11	0.94	9.41	6.52
Sample point 6	0.08	0.98	13.06	9.05
Sample point 7	0.07	0.97	13.85	9.60

Nutrient Use Efficiency (NUE) offers valuable insights into the effectiveness of nutrient utilization and allocation strategies (Fig. 8). NUE values demonstrate a diverse range, highlighting differential carbon use efficiency across the ecosystem. Sample point 1 displayed a distinctive pattern, with the NUE percentage escalating from May to January and reaching 50.92%, suggesting a more efficient carbon utilization during these months. Sample point 2 exhibited notable variability, with higher NUE percentages observed in July and September, indicating potential optimization of carbon use during these periods. Sample points 3, 4, and 5 portrayed consistent NUE patterns, with fluctuations within a certain range across different months. Sample point 7 showed an intriguing trend, with NUE percentages fluctuating significantly between January and March, indicating varying degrees of carbon use efficiency. The absence of NUE values in March for most sample points suggests a potential limitation in carbon utilization.

Sample point 7 is particularly intriguing, with notably high NUE percentages in September and November, suggesting an efficient utilization of Nitrogen during these periods. However, this efficiency contrasts sharply with November for sample point 1, where NUE drops to zero, potentially indicating a shift in nitrogen dynamics or availability. Sample points 2 to 6 exhibit varying NUE percentages over the months, with differing levels of nitrogen utilization efficiency. The absence of NUE values for January and March implies potential limitations or shifts in nitrogen utilization during these months.

Sample point 1 demonstrates a distinct pattern, with NUE percentages progressively increasing from May to January and subsequently surging to 53.85%, suggesting an enhanced phosphorous utilization during these months. Similarly, sample point 7 showcases a remarkable increase in NUE from January to March, potentially indicating a shift in phosphorous dynamics. Sample points 2 through 6 exhibits varying NUE percentages over the months, reflecting differences in phosphorous utilization efficiency. The absence of NUE values in March suggests potential limitations or shifts in potassium utilization during that period.

Sample point 1 experiences a gradual increase in NUE percentages from May to January, potentially indicating an improved potassium utilization strategy. Similarly, sample point 7 displays a remarkable surge in NUE from January to March, suggesting a shift in potassium dynamics. Conversely, sample points 2 to 6 exhibit fluctuating NUE percentages over the months, highlighting diverse potassium utilization strategies. The absence of NUE values in March implies potential limitations or changes in potassium utilization.

Nutrient Accumulation Index (NAI) provides a comprehensive perspective on the accumulation and distribution of carbon resources over time (Fig. 9). Sample points 3, 4, 5, and 6 demonstrate consistent increases in NAI percentages, suggesting a progressive accumulation of carbon content during the study period. Conversely, sample point 1 displays a fluctuating pattern, while sample point 7 showcases fluctuations followed by a decline in March.

Sample points 3 and 6 exhibit consistent increases in NAI percentages, indicating a continuous buildup of nitrogen content throughout the study period. In contrast, sample points 4 and 5 display more modest variations in NAI percentages, suggesting stable nitrogen accumulation. Sample points 1, 2, and 7 present unique profiles with fluctuating NAI values and, in some cases, minimal accumulation during certain months.

Sample points 6 and 7 exhibited consistent increases in NAI percentages, indicating a continuous buildup of phosphorus content throughout the study period. In contrast, sample points 1, 2, and 3 show fluctuating NAI values, suggesting variations in phosphorus accumulation influenced by environmental factors and plant nutrient uptake dynamics. Sample points 4 and 5 display stable NAI percentages, indicating a consistent phosphorus accumulation pattern.

Examining the sample points, distinct trends in NAI values emerge, highlighting diverse strategies for potassium accumulation. Sample points 1, 4, and 7 exhibit upward trends in NAI percentages, suggesting a consistent potassium accumulation over the study period. Conversely, sample points 2, 3, 5, and 6 show fluctuating patterns, potentially reflecting environmental and plant nutrient uptake dynamics variations.

Nutrient Retranslocation Efficiency (NRE) represents a critical aspect of ecosystem nutrient cycling, shedding light on how efficiently nutrients are remobilized from senescent leaves and reabsorbed before leaf shedding (Fig. 10). For Carbon among the sample points, NRE values ranged from 8.52–18.51%, displaying diverse nutrient retranslocation efficiencies. Sample point 7 exhibited the highest NRE of 18.51% in May, indicating substantial reabsorption of nutrients from litter fall. Conversely, sample point 3 displayed the lowest NRE of 8.52%, implying a comparatively lower efficiency in nutrient remobilization.

Figure no 10: Nutrient retranslocation efficiency (NRE) %

The NRE percentages, ranging from 15.98–57.98%, unveil dynamic variations in the nutrient retranslocation efficiency of Nitrogen. Sample point 5 stands out with notably high Nitrogen NRE values, reaching 85.48% in November, indicating efficient nitrogen remobilization from senescent leaves before shedding. In contrast, sample point 3 displayed relatively lower NRE values, starting from 18.77% in May and gradually increasing to 74.47% in November. Sample point 2 and sample point 7 showcased consistent NRE patterns, with values ascending from 53.75% and 56.07% in May, respectively, to nearly 100% in subsequent months, suggesting efficient nutrient reabsorption during later stages of decomposition. Sample point 1 displayed consistent 100% NRE values for January and March, suggesting complete nitrogen reabsorption during these months.

Among the sample points, NRE values exhibited a wide range from around 7.70–50.71%, demonstrating diverse strategies for phosphorus retranslocation. Sample point 4 stood out with notably high NRE values, reaching 50.71% in July, indicating efficient phosphorus remobilization from senescent leaves. In contrast, sample point 7 displayed relatively lower NRE values, particularly in January and March, suggesting less efficient phosphorus reabsorption during these months.

Sample points 2, 3, 4, and 6 are notably high NRE percentages, indicating efficient potassium remobilization. In contrast, sample point 1 displayed negative NRE values in May, indicating a potential potassium loss during that period. Sample point 7 showcased interesting NRE patterns, fluctuating over the months. Notably, in January, NRE dropped to 60.74%, suggesting less efficient potassium reabsorption during that month.

Abiotic factors and their relationship with leaf litter dynamics

Water holding capacity (0.73), moisture content (0.757), soil carbon content (0.766), soil nitrogen content (0.761), and humidity (0.726) showed a correlation with Decomposition rate in Pearson correlation analysis. The pH of the soil was investigated for its potential influence on several factors, and the F-statistics were employed to determine the significance of these effects. The results showed that soil pH had a significant impact on several parameters. Notably, there were significant associations between soil pH and the factors "Decomposition rate and "soil carbon content" ($F = 4.204$ and $F = 7.796$, respectively; all $p < 0.01$). This suggests that variations in soil pH levels correlate with parameter changes.

The initial eigenvalues for the components reflect their respective abilities to explain variance independently (Fig. 11). The first principal component exhibited the highest eigenvalue of 10.77, signifying its substantial impact in capturing the dataset's variability. The subsequent components, with eigenvalues of 6.66, 4.09, and 1.21, contributed successively less to the total variance. The extraction sums of squared loadings illustrate the variance captured by each principal component after transformation. The first component retained a massive portion of the variance at 39.90%, with subsequent components explaining 24.66%, 15.16%, and 4.48%, respectively. Together, these components cumulatively accounted for 84.22% of the total variance. Orthogonal rotation was applied to enhance interpretability, resulting in the rotation sums of squared loadings. The first component retained its dominance in explaining variance, contributing 39.90% of the total after rotation. The second, third, and fourth components accounted for 24.66%, 15.16%, and 4.48% of the variance after rotation (Table 3).

Table 3
Total Variance Explained for PCA analysis.

PCA	Eigen Value	% of Variance	Cumulative %
1	10.773	39.902	39.902
2	6.661	24.669	64.570
3	4.093	15.161	79.731
4	1.212	4.489	84.220

The Principal Component Analysis (PCA) results indicate key relationships between soil and environmental parameters and the primary PCA component. PC1 showed strong positive correlations with mass loss % (0.863), NRE potassium (0.744), and soil potassium (0.814). PC2 was correlated with decomposition rate (K_L) (0.858), humidity (0.865), water holding capacity (0.802), moisture content (0.802), soil carbon (0.763), and soil nitrogen (0.722). Rotated component matrices are essential to understand the underlying structure of complex datasets. The rotated component matrix obtained from the PCA analysis provides valuable insights into the relationships between variables and the underlying structure of the data (Table 4). Principal Component 1 (PC1) is influenced by variables such as Decomposition Rate (K_L), pH, Water holding capacity, Moisture content, Soil organic carbon, soil carbon, soil nitrogen, soil phosphorous, soil potassium, and humidity. PC2 reflects contributions from Decomposition Rate (K_L), NUE carbon, NUE phosphorous, NUE potassium, NAI carbon, NAI phosphorous. PC3 reflects contributions to mass loss %, NRE carbon, NRE nitrogen, NRE potassium. The result indicates that pH (0.812), water holding capacity (0.924), moisture content (0.944), soil organic carbon (0.772), soil carbon (0.893), soil nitrogen (0.857), soil phosphorous (0.847), and soil potassium (0.726) and humidity (0.836) significantly influence Litter Decomposition in Sal Forest ecosystem.

Table 4
PCA component correlation with litter dynamics of Sal Forest.

Parameters	Component Matrix Correlation	Rotated Component Matrix
Mass loss %	0.863	0.945
NRE *(Carbon)*		0.784
NRE *(Nitrogen)*		0.910
NRE *(Potassium)*	0.744	0.735
Decomposition rate (K_L)	0.858	0.865
NUE *(Carbon)*		0.974
NUE *(Nitrogen)*		0.966
NUE *(Potassium)*		0.883
NAI *(Carbon)*		0.970
NAI *(Potassium)*		0.954
pH		0.812
Water Holding Capacity	0.803	0.924
Moisture Content	0.802	0.944
Soil Organic Carbon		0.772
Soil Carbon	0.763	0.893
Soil Nitrogen	0.722	0.857
Soil Phosphorous		0.847
Soil Potassium	0.814	0.726
Humidity	0.865	0.836

Discussion

The leaf litter dynamics encompasses a multifaceted interaction between litterfall, decomposition rates, and abiotic factors. These interactions collectively sculpt nutrient cycling and ecosystem processes. The shedding of leaves is a pivotal phenological event that marks the transition between seasons. This event is documented by Misra (1969) and typically starts from the late winter months, notably February, until mid-April. Recent studies (Nandy et al., 2021) have further refined our understanding, estimating the onset of the growing season for Sal trees to be around mid-May. Litter production rates exhibited significant spatial and temporal variability within the study area. Specifically, January to May witnessed the highest accumulation of fallen litter. When comparing samples 5 and 6, which both feature mixed natural vegetation, it becomes evident that a significant amount of litter is generated. This observation is consistent with the research conducted by Wang et al. (2007), which documented a higher rate of litter production in mixed plantations and diverse wild vegetation as opposed to monoculture crop stands. These observations substantiate the profound influence of phenology and vegetation composition on litter production.

Liu et al. (2020) highlighted that mixed-species litter decomposition outpaces the decay rates of single-litter species by 3–5%. The remarkable turnover rate witnessed at sample point 6 in March accentuates significant litter transformation because of the prominent role of seasonal cues and microenvironmental like pH, Water holding capacity, Moisture content, Soil organic carbon, soil carbon, soil nitrogen, soil phosphorous, soil potassium, and humidity in regulating decomposition.

The study reveals intricate connections between soil and environmental parameters and their impact on litter decomposition in the Sal Forest ecosystem. Key findings include significant correlations between decomposition rate and variables such as water holding capacity, moisture content, soil carbon, soil nitrogen, and humidity. Soil pH emerges as a critical factor, significantly influencing both decomposition rate and soil carbon content. Principal Component Analysis identifies two primary components: PC1, highlighting the importance of mass loss percentage and potassium-related variables, and PC2, emphasizing decomposition rate, humidity, and nutrient dynamics. This study underscores the multifaceted nature of litter decomposition, highlighting the substantial influence of abiotic factors and nutrient cycling processes within the ecosystem. Abiotic factors have a profound influence on litter dynamics. As Qualls (2000) mentioned, moisture levels play a dual role, facilitating microbial activity and rainfall-induced nutrient leaching, which might decelerate decomposition. As Hector et al. (2000) detailed, sunlight exposure, wind patterns, and soil moisture affect decomposition rates within specific microenvironments, adding a layer of complexity to the process. The nutrient content of litter serves as a crucial driver, as observed by Gusewell and Gessner (2009), where higher nitrogen and phosphorus content leads to faster decomposition. The C: N ratio, as identified by Chen et al. (2014), emerges as a governing factor, with narrower ratios favoring accelerated microbial activity. pH, a reflection of soil conditions, shapes microbial communities and enzymatic activity, consequently impacting decomposition (Batty & Younger, 2007). The study also acknowledged that meteorological data was not robust. Additionally, it is important to note that microbial activities, which can significantly influence decomposition rates, were not considered in this analysis. These factors underscore the complexity of litter decomposition processes and suggest that future research should consider a more comprehensive approach.

This study was done to understand the letter dynamics in the Sal Forest. The study was carried out for one year in 7 different locations. The result obtained from this analysis was in coordination with the above findings. The Sal tree's phenology and the area's climatic condition influenced the litter production dynamics. Sample point 6 has the highest vegetation cover and maximum mixed vegetation among the different sample areas. This sample point showed the best result regarding litter decomposition, nutrient accumulation, and nutrient utilization. May, June, and July were the most favourable for litter decomposition. Thus, the litter decomposition rate in these months was comparatively higher than the rest of the month. Regarding soil property pH, water holding capacity, moisture content, soil carbon, soil nitrogen, and soil phosphorous played a significant role. Therefore, it is justified that litter decomposition is a multifaceted process influenced by many interacting factors.

Conclusion

The results gleaned from the study of decomposition rates shed light on the intricate interplay between organic matter breakdown and soil health with significant implications for nutrient availability, carbon sequestration, and overall ecosystem health. The data reveals distinct patterns of decomposition rates across different sample points and months, underscoring the heterogeneity of decomposition dynamics within the studied ecosystem. Sample point 6 has consistently higher decomposition rates, suggesting a potential combination of favorable conditions. The results collectively emphasize the complex nature of nutrient dynamics within the leaf litter ecosystems. The variations observed in nutrient accumulation, retranslocation, and use efficiency underscore the intricate interplay between biological processes and environmental conditions. These findings have far-reaching implications for ecosystem health, nutrient cycling, and productivity. Understanding these nutrient dynamics is essential for sustainable land management practices, as they provide critical insights into the functioning of ecosystems and can guide efforts to enhance nutrient utilization efficiency and maintain ecological balance. The identified correlations, significant influences of soil pH, and principal component analysis results collectively highlight the importance of considering a comprehensive approach to ecosystem management.

Abbreviations

Nutrient accumulation index (NAI)

Nutrient Retranslocation Efficiency (NRE)

Nutrient use efficiency (NUE)

Declarations

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Availability of data and material: Not applicable

Code availability: Not applicable

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Figures

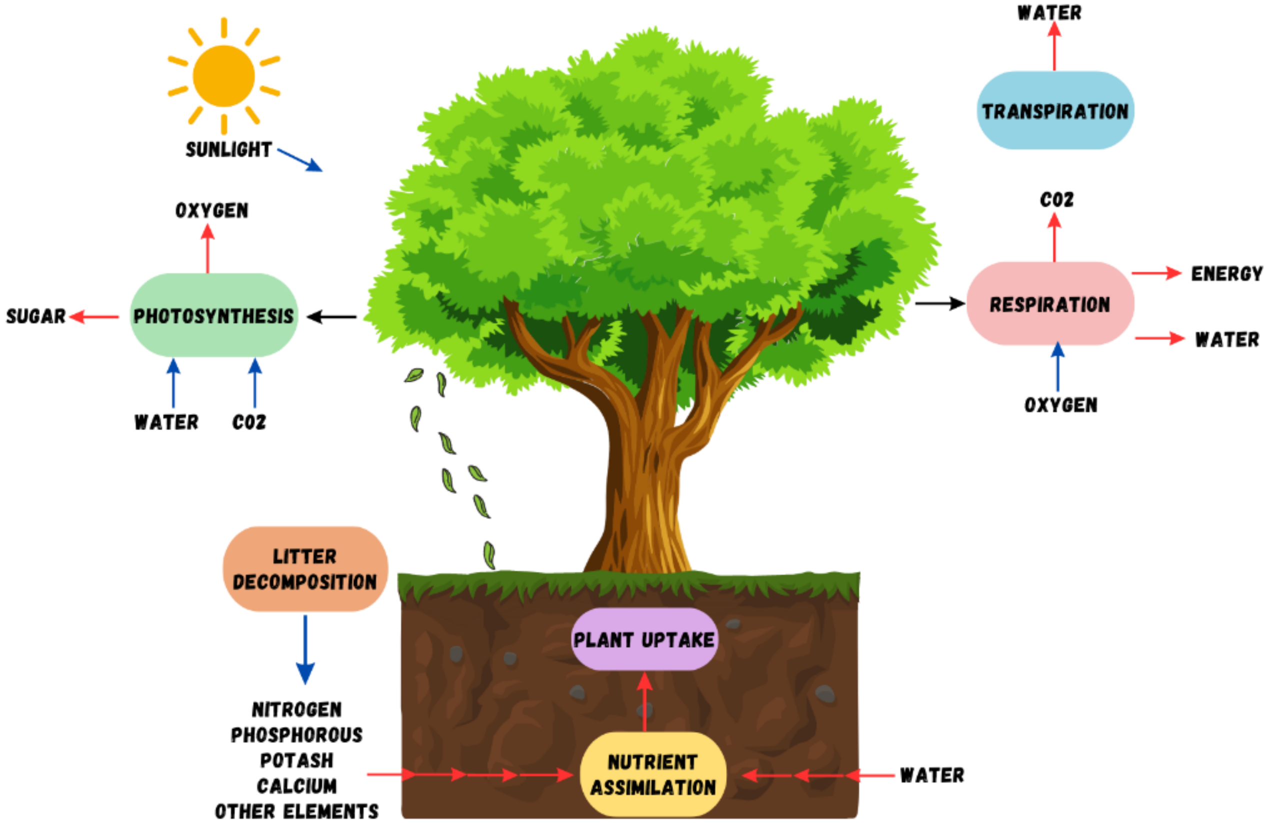

Figure 1

Physiological processes and their contribution to the nutrient cycling process in the forest ecosystem.

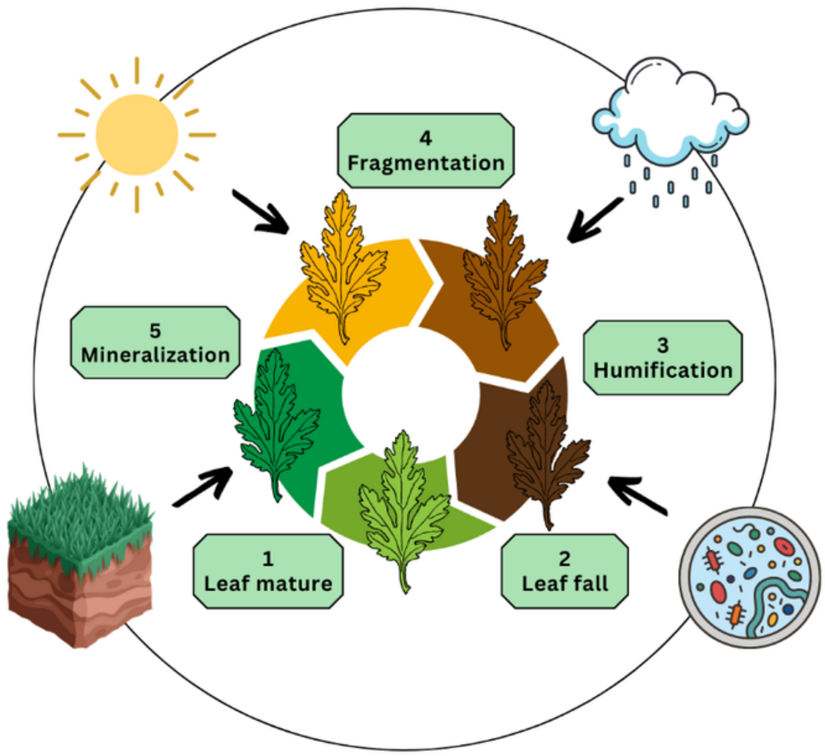

Figure 2

Leaf life cycle phases.

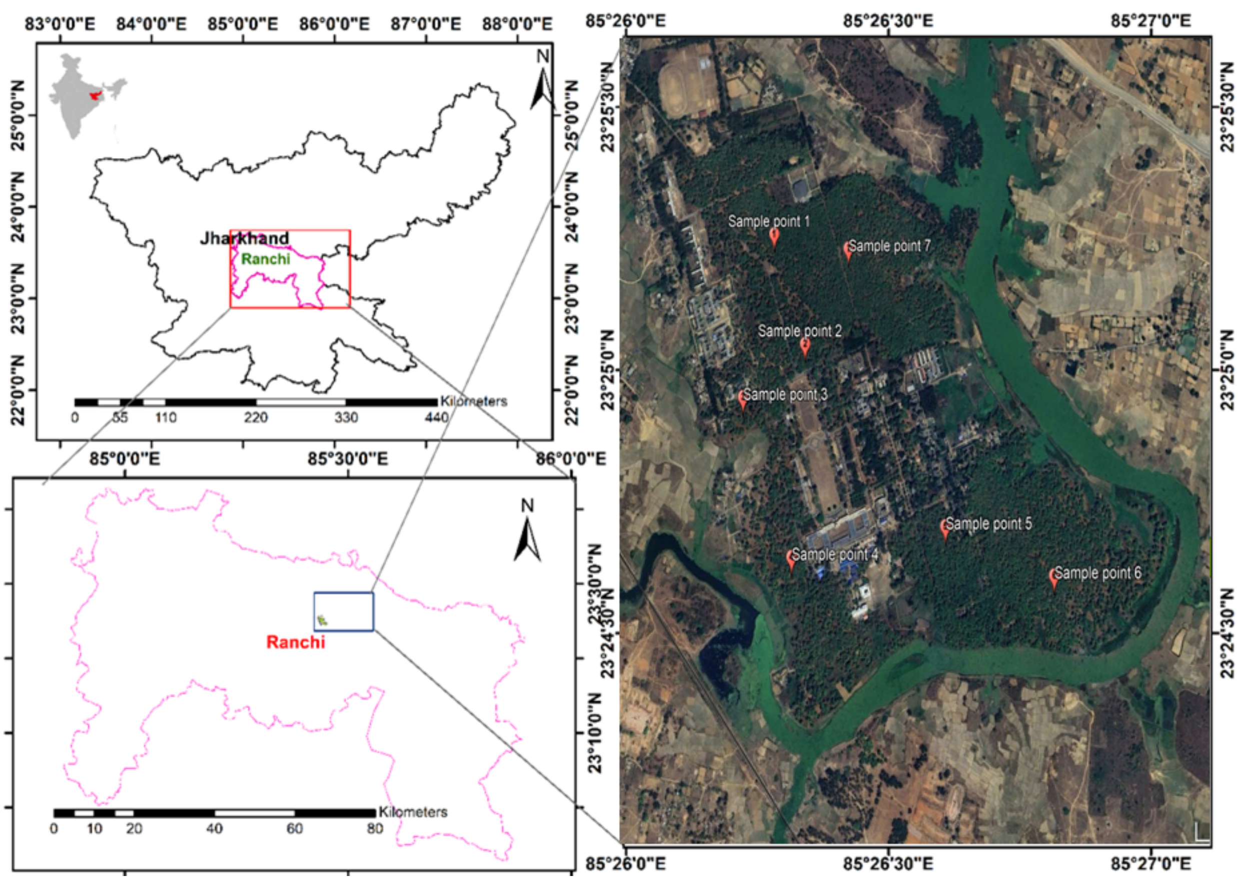

Figure 3

Study area.

Figure 4

Field sampling of Litterfall

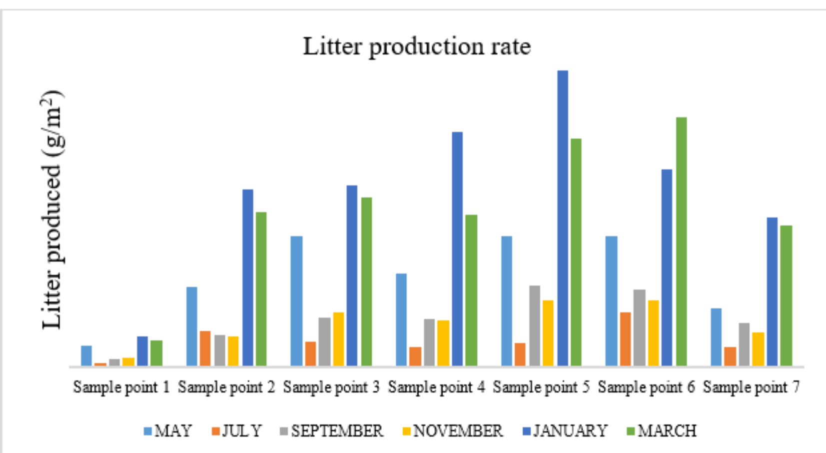

Figure 5

Litter produced throughout the year at different sample sites.

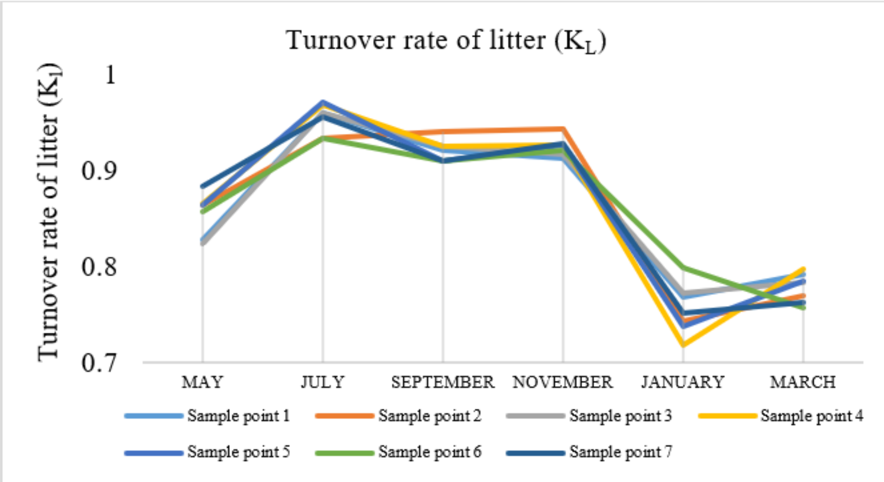

Figure 6

Turnover rate of litter (K_L) of different sample sites throughout the year.

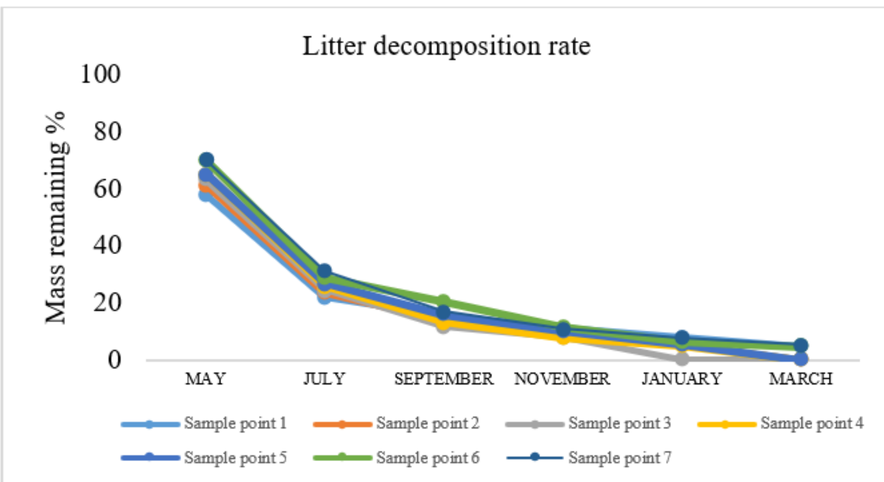

Figure 7

Litter decomposition rate of sample points throughout the year.

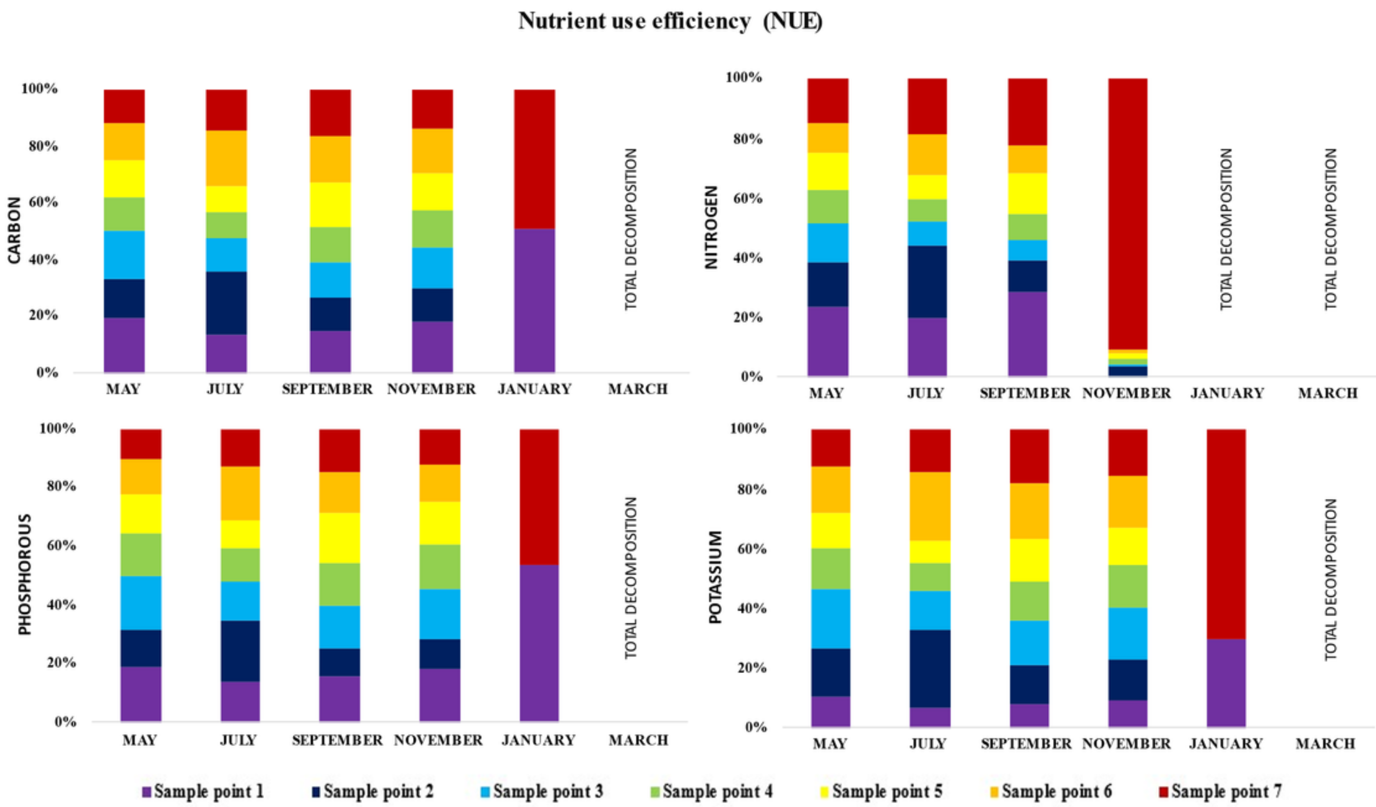

Figure 8

Nutrient use efficiency (NUE)

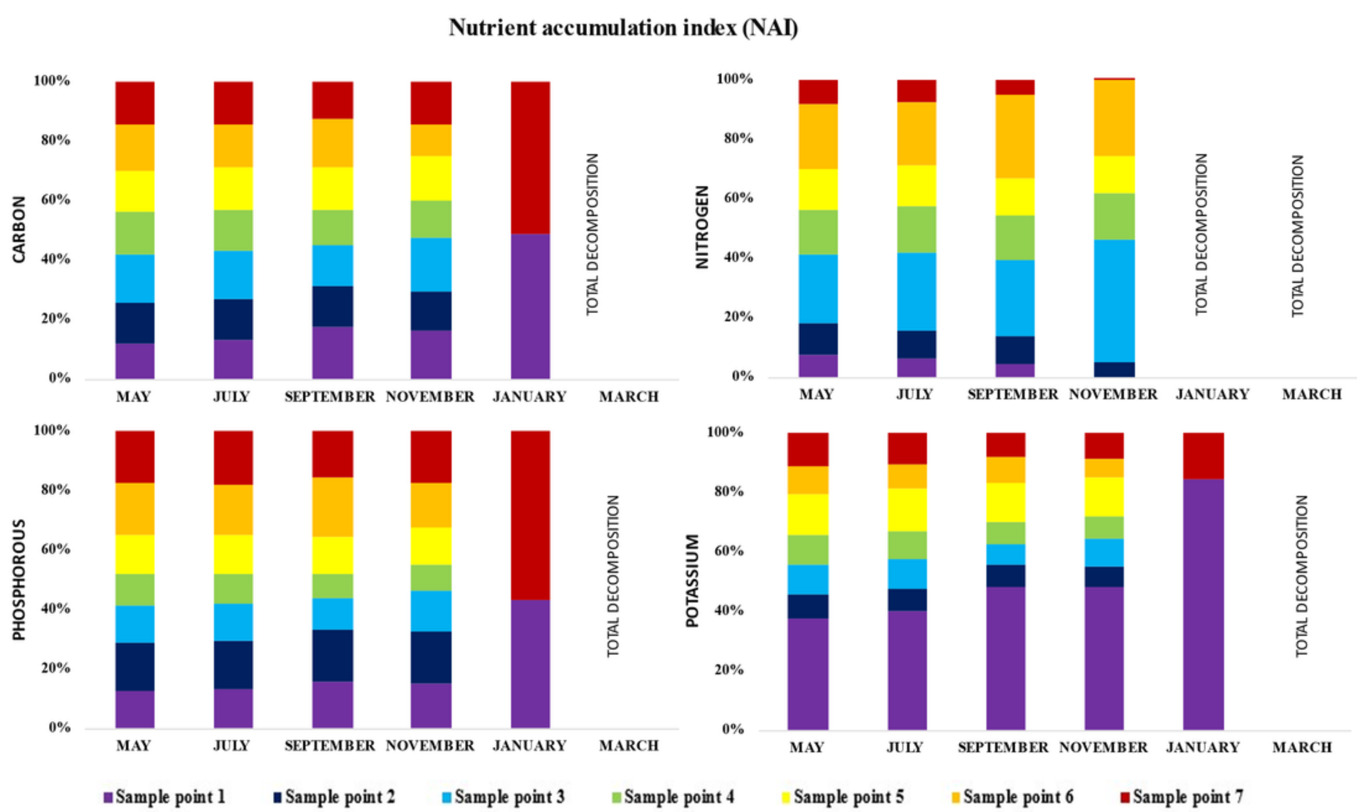

Figure 9

Nutrient accumulation index (NAI)

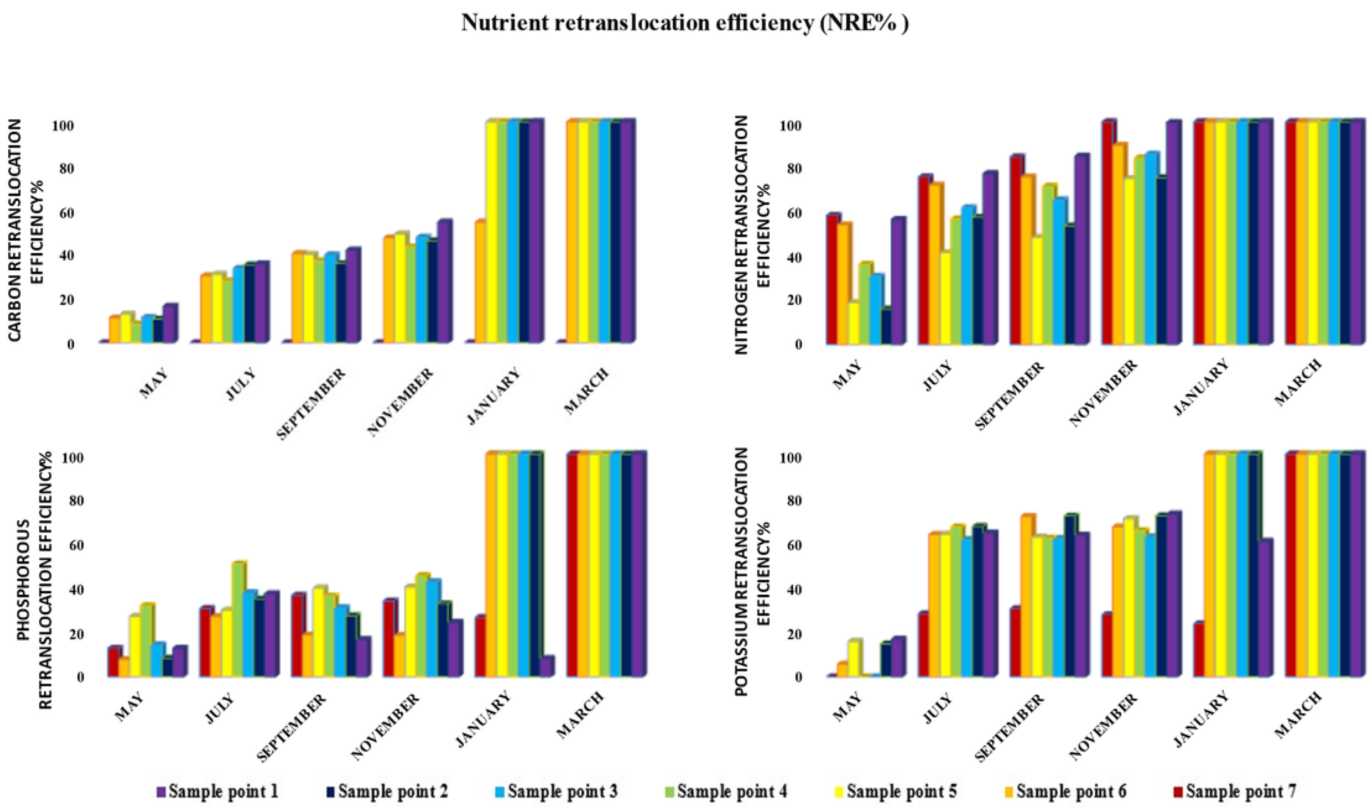

Figure 10

Nutrient retranslocation efficiency (NRE) %

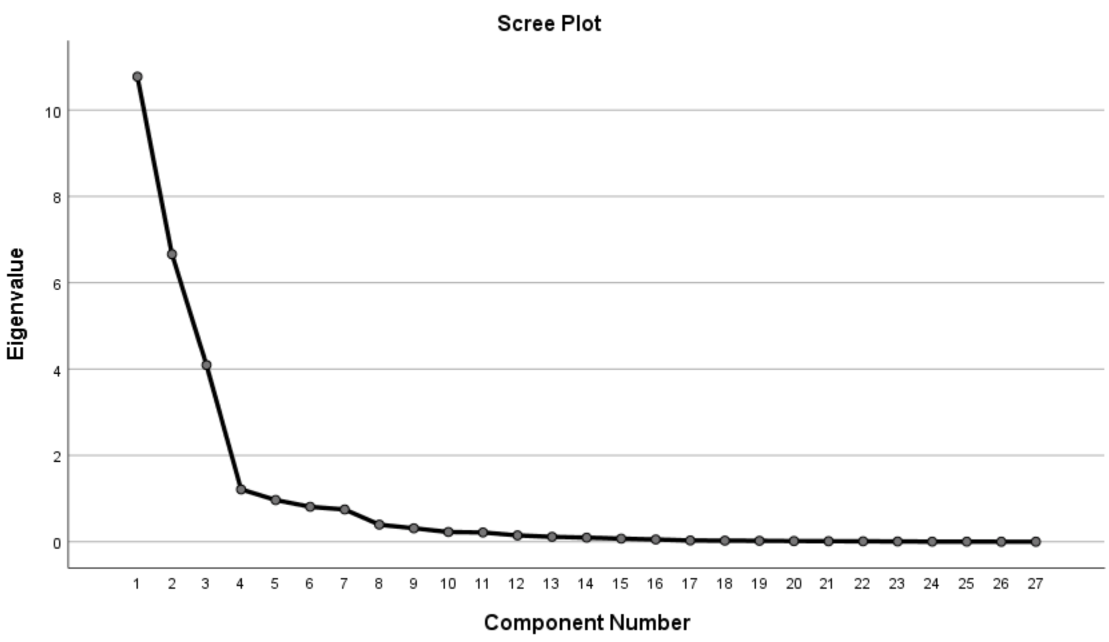

Figure 11

Scree plot of PCA analysis.