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Article

Leaf litter decomposition and carbon release patterns in five homegarden trees species of Kumaun Himalaya, India

Vibhuti, Archana Fartyal, Kiran Bargali, Surendra Singh Bargali*

Department of Botany, DSB Campus, Kumaun University, Nainital-263002, Uttarakhand, India
* **Corresponding author:** Surendra Singh Bargali, surendrakiran@rediffmail.com

Abstract: Leaf litter decomposition and carbon release patterns in five homegarden tree species of Kumaun Himalaya viz. *Ficus palmata* Forssk., *Ficus auriculata* Lour., *Ficus hispida* L.f., *Grewia optiva* L. and *Celtis australis* L. were investigated. The study was carried out for 210 days by using the litter bag technique. In the current investigation, the duration needed for desertion of the original biomass of diverse leaf litter varied from 150 to 210 days and specifies a varying pattern of decomposition and carbon release among the species. *Grewia optiva* took the longest time to decompose (210 days), while *Ficus hispida* decomposed more quickly than the rest of the species (150 days). The relative decomposition rate (RDR) was reported to be highest in *Ficus hispida* (0.009–0.02 $g^{-1}d^{-1}$) and lowest in *Grewia optiva* (0.008–0.004 $g^{-1}d^{-1}$). Carbon (%) in remaining litter was in the order: *Ficus auriculata* (24.4%) > *Ficus hispida* (24.3%) > *Celtis australis* (19.8%) > *Ficus palmata* (19.7%) > *Grewia optiva* (19%). The relationship between percentage weight loss and time elapsed showed a significant negative correlation with carbon release pattern in all the species. Releasing nutrients into the soil through the decomposition of homegarden tree residual is a crucial ecological function that also regulates the nutrient recycling in homegarden agroforestry practices.

Keywords: carbon release pattern; homegarden agroforestry; litter decomposition; relative decomposition rate

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1. Introduction

Litter decomposition is the process by which organic matter breaks down, loses structural integrity, and ultimately mineralizes into basic components, including water (H_2O), carbon dioxide (CO_2), and other mineral elements (Fu, 2025; Zhao et al., 2025). Litter is an important constituent of nutrient cycling and the rates and pathways of litter decomposition are determined by weather patterns, properties of soil, substrate quality, and the overall structure of the decomposing organisms' community (Manral et al., 2023; Fu, 2025; Zhao et al., 2025). During the course of the process, dissolved organic carbon may leach to the mineral soil and refractory organic compounds may be generated. Furthermore, it is widely acknowledged that there are three primary ways in which decomposition takes place: (1) soluble materials leaching into the soil, (2) fragmenting litter into tiny fragments, and (3) breakdown by decomposing agents (i.e. microbes, micro-organisms and animals) (Joly et al., 2023). Decomposition rate and nutrient release pattern are specific to a species and are associated with quality, including seasonal variation, chemical constituents of litter, and ecological conditions (Sarkar et al., 2016).

A positive feedback loop between nutrient mineralization and litter quality may be established through decomposition processes (Bargali et al., 2015a; Yang et al., 2022). Fast decomposition rates aid in meeting plant intake requirements, whereas slow decomposition rates cause organic matter and nutrient stocks to accumulate in the soil (Isaac and Nair, 2005). Temperature, precipitation, and seasonal variations are examples of climate characteristics that can alter the presence of bacteria and other soil fauna (Manral et al., 2023), which in turn can have a substantial impact on the rate of decomposition. The processes and communities in the soil that are active during decomposition are also influenced by litter diversity (Chapman and Koch, 2007). The primary functions of soil microorganisms are to break down plant wastes and release nutrients (Zhang et al., 2025). This procedure is crucial for preserving and maintaining soil fertility as it promotes the configuration of soil organic matter and the cycling of nutrients (Upadhyay and Singh 1989; Bargali et al., 1993; Usman et al., 2000; Singh et al., 2007; Guendehou et al., 2014).

The age-old practice of homegarden agroforestry combines the cultivation of trees with crops and livestock that can help to solve the problem of land degradation by preserving soil quality and preventing soil erosion. The chemical composition of various plant litter types is unique to each species (Bargali et al., 2006; Nath and Das, 2011; Ma et al., 2025). Decomposition occurs differently in agroforestry systems than it does in natural forests and agricultural systems, due to variations in the nature and quality of organic inputs (Mafongoya et al., 1998; Bargali, 2015). Several workers have carried out studies on plant diversity, utilization patterns and ecosystem services provided by homegarden agroforestry systems (Bargali, 2015; Vibhuti et al., 2018; Akoijam et al., 2025) in the Himalayan regions of India, but so far only a few records of leaf litter decomposition have been found. Thus, in this study, an effort has been made to analyse the decomposition pattern and carbon release from leaf litter of five common Homegarden tree species of Kumaun Himalayan region, India. The main objective of this study is to find out the leaf decay rate of the selected tree species to comprehend their role and contribution towards the carbon cycle in homegardens.

2. Materials and methods

2.1. Study area

The current investigation was carried out in the home gardens of the Kumaun Himalaya in Uttarakhand, India. The Northwestern portion of the Central Himalayan area is made up of the Kumaun Himalaya, which is geographically located at 28°44'-30°49' N and 78°45'-85°5' E. The selected study site is located at 29°19'10.84" N latitude and 79°31'24.20" E longitude between the altitudes of 350 and 700 m above mean sea level.

2.2. Climate

The weather conditions during the study period (December 2015 to June 2016) were recorded (Climate Uttarakhand, 2017). The minimum temperature was 16 °C in the month of December, whereas the maximum temperature was 32 °C in the month of June. The maximum rainfall was 632 mm in June (**Figure 1**).

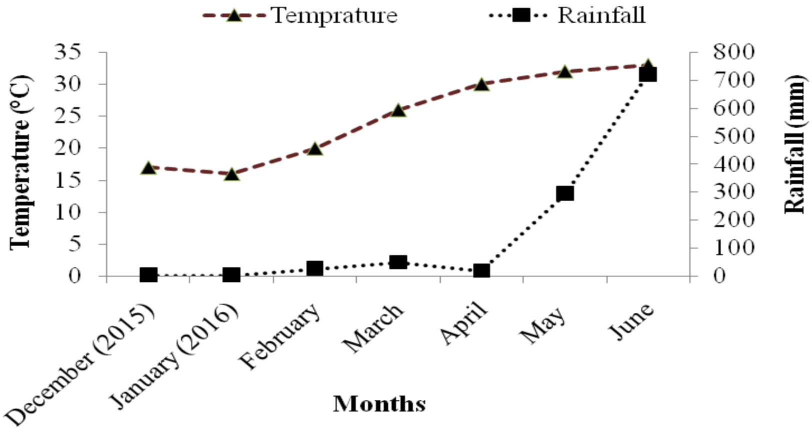


Figure 1. Meteorological data of the study sites (Source: https://www.weather.ind.com).

2.3. Soil characteristics

In the study site, the soil was sandy in texture. The proportion of sand, silt and clay was 50.17%, 32.53% and 17.75%, respectively. Bulk density was 0.95 g cm^{-3}. The water holding capacity of the soil was 62.49%. pH of the soil was 7.27, which was alkaline in nature. Soil contains 3.69% carbon, 0.34% nitrogen and 0.14% phosphorous.

2.4. Data collection

Freshly fallen leaves of selected tree species (*Ficus palmata, Ficus auriculata, Ficus hispida, Grewia optiva* and *Celtis australis*) were collected and air-dried. Nylon net bags measuring 10 cm × 10 cm were used to quantify decomposition rate. Each litter bag contained 10 g of air-dried leaf material. Three sample portions of each species were oven-dried to assess the initial moisture content of the litter at the time of field placement. In December 2015, 105 litter bags per species were placed individually in the field, taking care to minimize disturbance to the forest floor while ensuring the bags remained in contact with the soil. Three litter bags belonging to each species were retrieved at random monthly intervals starting in December 2015, and continued until approximately 95% decomposition was observed. The retrieved litter bags were separately packed in polyethylene bags and transported to the laboratory immediately. The remaining litter material was carefully separated from the adhering soil particles using a small brush, oven dried at 60 °C to constant weight, and the dry weight of the leaf material was recorded.

2.5. Litter mass loss and decay rate coefficient

The difference between the mass of litter in the litterbags at the end of a given month and the bulk of litter in the bags the month before was used to calculate the monthly mass loss (g $month^{-1}$) from decaying litter. The average daily decomposition percentage, the total number of days the sample was in the woods and the Decay Constant were computed in accordance with Petersen and Cummins (1974) as follows:

$$(k) = -k = \mathrm{Ln}\ (\%\ R/100)/t$$

Where, t is the time in days

The percentage of material remaining (% R) after a specified amount of time was used to describe the rate of litter material loss and calculated following Petersen and Cummins (1974) as:

$$\%\ R = W\ (tx)/W\ (ti) \times 100$$

where W (tx) is the dry weight (g) of the leaf material after time (tx), and W (ti) is the initial weight of the leaf material.

In the present study,% R was computed monthly as well as for the entire period.

The mean relative decomposition rate (RDR) was computed by using the formula:

$$\mathrm{RDR}\ (g\ g^{-1}\ day^{-1}) = \ln\ (w^1 - w^0)/(t^1 - t^0)$$

Where, w^0 = mass of litter present at time t^0; w^1 = mass of litter present at time t^1; $t^1 - t^0$ = sampling interval (days)

2.6. Carbon release pattern

Carbon in leaf litter was analysed following Walkley and Black (1934). The monthly release pattern of carbon (C) from the leaf litter was analyzed by the differences in carbon amounts from the first month to the following month and the net release was calculated by summing up the carbon release for the entire duration. Correlation and regression were computed following Snedecor and Cochran (1969).

Carbon content of the decomposing leaf was derived from the equation:

$$\%\ \text{Carbon remaining} = \left(\frac{C}{C_0}\right) \times \left(\frac{DM}{DM_0}\right) \times 10^2$$

Where, C is the concentration of the element in the leaf litter at the time of sampling, C_0 is the concentration of the initial litter kept for decomposition; DM is the mass of dry matter at the time of sampling, and DM_0 is the initial dry matter of the litter sample kept for decomposition (Bockheim et al., 1991).

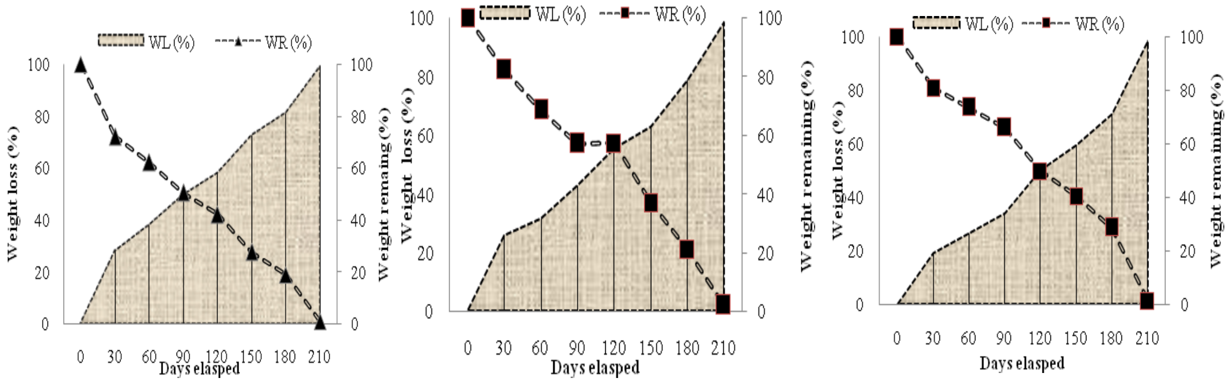
2.7. Statistical analysis

All the statistical analyses were carried out using SPSS 16.0 software. Pearsons' correlation analysis was performed to examine the relationships between the percent weight loss of leaf litter and environmental variables, including days elapsed, temperature, and rainfall. In addition, simple linear regression analysis was conducted to quantify the relationship between percent weight loss (dependent variable) and each environmental factor (independent variables: days elapsed, rainfall, and temperature).

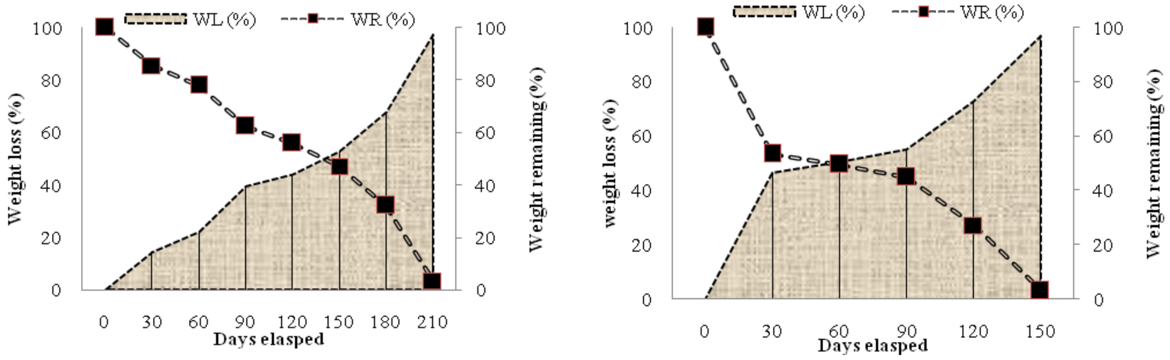
3. Results

3.1. Weight loss pattern

In the first month (30 days), maximum weight loss was observed in *F. hispida* (46.57%), followed by *F. auriculata* (27.97%), *F. palmata* (25.80%), *C. australis* (19.10%) and minimum weight loss was recorded in *G. optiva* (14.37%). Initially, weight loss progressed slowly during December–February, followed by a rapid phase (March onwards). Over the total observation period, the highest cumulative weight loss was recorded in *G. optiva* (97.50% within 210 days) and slightly lower in *F. hispida* (96.86% within 150 days), indicating differences in decomposition rates. The decay constant (k) was highest for *F. hispida* (0.02), followed by *F. auriculata, F. palmata* and *C. australis* (0.01), and lowest for *G. optiva* (0.005) in the first month. Maximum weight loss was observed during the summer (April and June) seasons as compared to the winter season (December to March) (**Figure 2**).



Ficus auriculata *Ficus palmata* *Celtis australis*



Grewia optiva *Ficus hispida*

Figure 2. Percent weight loss and remaining leaf litter (% of the original) in five homegarden tree species (where, WL = weight loss; WR = weight remaining).

3.2. Remaining weight pattern

The decomposition values, reported as the mean percentage of dry weight remaining for each sample interval, showed the decay rates of foliar litter from the selected species. **Figure 2** depicts the remaining mass (% of the original) of leaf litter of diverse species in recovered litter bags on a monthly basis. In the first month (30 days), the highest remaining litter percentage was recorded in *G. optiva* (85.63%), followed by *F. palmata* (82.3%), *C. australis* (80.90%), *F. auriculata*

(72.03%) and the lowest in *F. hispida* (53.43%). By the final month, the maximum remaining weight (%) was observed in *G. optiva* (3.5% within 210 days), while the minimum was in *F. hispida* (3.13% within 150 days (**Figure 2**).

3.3. Relative decomposition rate (RDR)

The monthly relative decomposition rate (RDR) was maximum for *F. hispida* (0.009–0.02 g^{-1} d^{-1}) followed by *F. auriculata* (0.009–0.01 g^{-1} d^{-1}), *F. palmata* (0.009–0.01 g^{-1} d^{-1}), *C. australis* (0.009-0.01 $g^{-1}d^{-1}$) and minimum in *G. optiva* (0.008–0.004 g^{-1} d^{-1}) (**Table 1**).

Table 1. Average decay coefficient (-k) and relative decomposition rate (RDR) of leaf litter in five homegarden tree species.

Days elapsed	**Species**									
	F. auriculata		***F. Palmata***		***C. australis***		***G. optiva***		***F. hispida***	
	−k	**RDR**	**−k**	**RDR**	**−k**	**RDR**	**−k**	**RDR**	**−k**	**RDR**
30	0.01	0.03	0.01	0.03	0.01	0.02	0.005	0.01	0.02	0.05
60	0.009	0.02	0.006	0.02	0.007	0.01	0.004	0.01	0.01	0.03
90	0.007	0.02	0.006	0.04	0.005	0.009	0.005	0.01	0.009	0.02
120	0.007	0.01	0.002	0.02	0.006	0.01	0.005	0.01	0.011	0.02
150	0.005	0.03	0.007	0.01	0.006	0.01	0.005	0.01	0.015	0.02
180	0.009	0.01	0.009	0.01	0.007	0.01	0.006	0.01	-	-
210	0.03	0.001	0.01	0.01	0.010	0.010	0.008	0.01	-	-

Where, −k = decay coefficient; RDR = relative decomposition rate

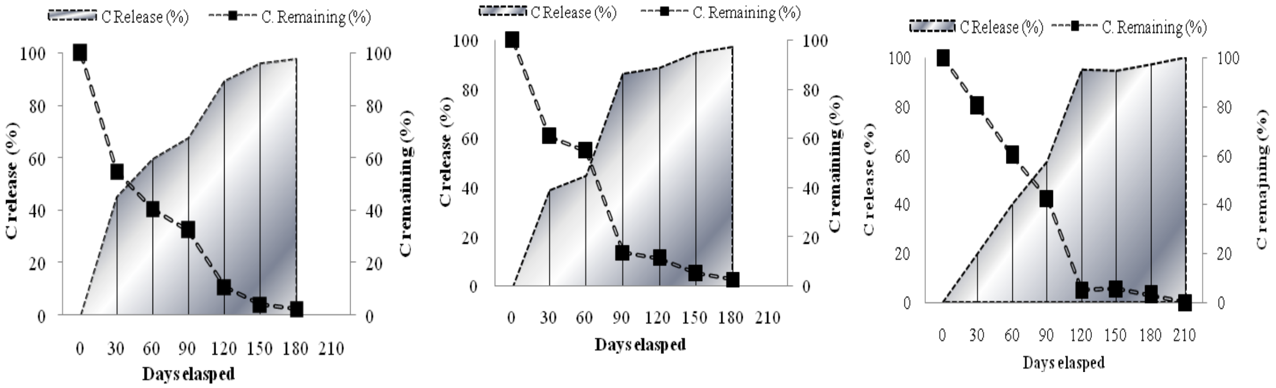
3.4. Carbon (%) in remaining litter and release pattern

Carbon percentage in remaining litter was maximum in *F. auriculata* (24.4%) and gradually followed by *F. hispida* (24.3%), *C. australis* (19.8%)*, F. palmata* (19.7%) and *G. optiva (*19%). Carbon content of litter decreased with increasing time duration (**Table 2**).

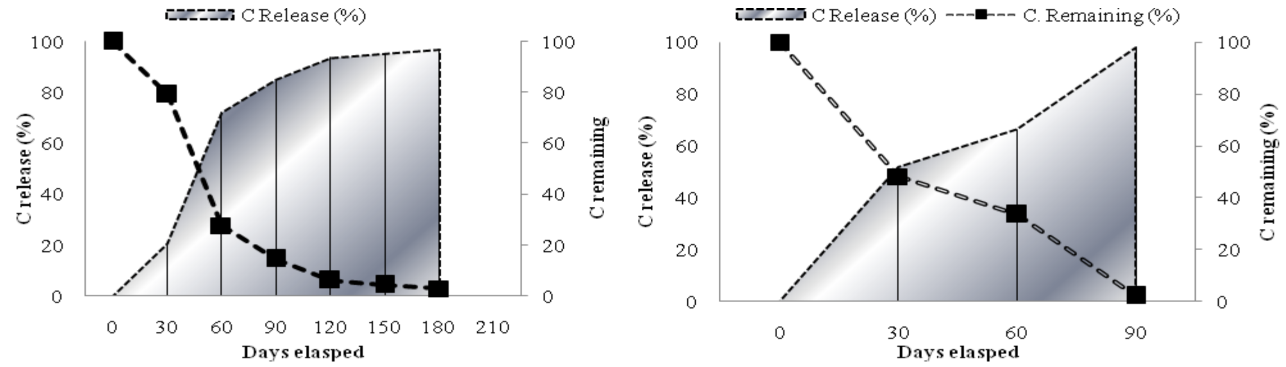
Table 2. Carbon (%) in leaf litter of five homegarden tree species.

Days elapsed	**Species**				
	F. auriculata	***F. Palmata***	***C. australis***	***G. optiva***	***F. hispida***
30	24.4	19.7	19.8	19	24.3
60	20.9	19.3	16.3	7.3	18.3
90	20.6	5.7	12.9	5	1.2
120	8.2	4.5	2	2.3	-
150	4.7	3.3	2.7	2	-
180	4	3	2	1.9	-
210	-	-	-	-	-

The release of carbon in the 90 days was faster in *F. palmata* (98%). During the same period, maximum carbon (%) was observed in *G. optiva* (84.24%) followed by *F. auriculata* (67.6%) and *C. australis* (57.43%). At 180 days, carbon release patterns were 97.7% for *F. auriculata*, 97.34% for *F. palmata*, 97.12% for *C. australis* and 97.02% for *G. optiva*. The carbon remaining pattern ranged from 48.06 (*F. hispida*) to 80.09% (*C. australis*) during 30 days. It was decreased with increasing day's period, which ranged from 0 to 2.98 during 180 days (**Figure 3**).



F. auriculata *F. palmata* *C. australis*



G. optiva *F. hispida*

Figure 3. Carbon release (%) and carbon remaining (%) pattern in decaying leaf litter of five homegarden tree species.

4. Discussion

4.1. Weight loss pattern

The mass of leaf litter steadily reduced during the experiment due to decomposition. The current study found that it took somewhere between 150 and 210 days for the original biomass of various leaf litter types to decompose completely. In comparison to other species, *F. hispida* decomposed more quickly (150 days), whilst *G. optiva* took the longest (210 days) to decompose completely. The varying rates of decomposition in selected tree species seemed to be influenced by differences in the morphological and chemical characteristics of their leaf litter (Sarkar et al., 2016; Pandey et al., 2024). Leaf litter decomposed rapidly during the first thirty days and then gradually lost mass over the subsequent 150 days (**Figure 2**). Barbhuiya et al. (2008) speculate that the rapid initial decomposition may be due to the high concentration of water-soluble components and simple substrates, which are readily broken down by decomposers. There was a substantial ($p < 0.05$) correlation between the percentage of weight reduction and the climate parameters in all the species except *F. hispida* (**Table 3**). Similarly, mass loss pattern and rate of decomposition showed significant correlation with days elapsed, possibly due to the chemical properties and quality of leaf litter, the presence of different concentrations of water-soluble phenolic compounds. These findings are consistent with observations in Central Himalayan Oaks (*Quercus leucotrichophora* A. Camus and *Quercus floribunda* Lindl.), where litter slowed over time (Padalia et al., 2015), and agroforestry species in the Southern dry agro-climatic zone of Karnataka, where mass loss patterns varied with species and season (Dhanya et al., 2013). Hasanuzzaman and Hossain (2014) reported that in the majority of common cropland agroforest horticulture tree species in Bangladesh, during the rainy season, there was a substantial ($p < 0.05$) increase in mass loss, rate of decomposition, decay constant, and quantity of nutrient return from leaf litter. While the results highlight the species exhibiting the fastest and slowest decomposition, as well as higher or lower carbon content in leaf litter, these observations should be interpreted as trends rather than statistically significant differences, since formal comparisons of means were not performed in this study. The observed variation among species likely reflects differences in leaf litter chemical composition, morphological traits, and susceptibility to microbial breakdown. For example, *F. hispida* showed relatively faster decomposition, whereas *G. optiva* decomposed more slowly, and similar trends were observed in carbon release patterns. Future studies with larger sample sizes and appropriate statistical analyses, such as ANOVA followed by post hoc tests, would be valuable to identify species with significantly higher or lower carbon content and decomposition rates. Despite this limitation, the observed trends provide meaningful insights into species-specific litter dynamics and their potential contribution to nutrient cycling and soil carbon accumulation in homegarden agroforestry systems.

Table 3. Relationship between days elapsed (DE), rainfall (RF), temperature (T) and weight loss (WL) of leaf litter in five homegarden tree species.

		a (intercept)	**b (slope)**	**R^2 (correlation coefficient)**
WL vs. DE	*F. auriculata*	6.59	0.35x	0.888^*
	F. palmata	2.85	0.37x	0.870^*
	C. australis	3.20	0.34x	0.859^*
	G. optiva	0.92	0.37x	0.929^*
	F. hispida	78.05	−0.26	0.254^{ns}
WL vs. RF	vs. *F. auriculata*	35.84	0.08x	0.846^*
	F. palmata	27.40	0.09x	0.896^*
	C. australis	30.87	0.08x	0.914^*
	G. optiva	25.66	0.08x	0.816^*
	F. hispida	62.31	−0.10x	0.646^*
WL vs. T	vs. *F. auriculata*	−27.21	3.07x	0.817^*
	F. palmata	−36.46	3.15x	0.716^*
	C. australis	−27.40	2.89x	0.744^*
	G. optiva	−42.06	3.26x	0.864^*
	F. hispida	94.614	−1.95x	0.167^{ns}

Where, * = significant at 0.05 level (2-tailed), ns = non significant; DE = days elapsed; RF = rainfall; T = temperature; WL = weight loss

4.2. Relationship between percent weight loss, days elapsed and environmental factors

Correlation analysis showed that, except for *F. hispida* (r = 0.254) percent weight loss had a significant ($p < 0.05$) positive correlation with days elapsed in all the species: *F. auriculata* (r = 0.888), *F. palmata* ($r^2 = 0.870$), *C. australis* (r = 0.859) *G. optiva* (r = 0.929). The same trend was also reported for temperature. In case of rainfall, percent weight loss recorded significant positive correlation for all species; *F. auriculata* (r = 0.846), *F. palmata* (r = 0.896), *C. australis* (r = 0.914) *G. optiva* (r = 0.816), except *F. hispida* (r = 0.646) (Table 3). Regression analysis indicated that the slope of the relationship between percent weight loss and days elapsed was highest for *G. optiva*, suggesting a relatively faster response of decomposition to time, while the intercept reflects the initial weight of litter at the start of the experiment. These results quantify how environmental factors influence decomposition rates and provide a mechanistic understanding of species-specific litter breakdown patterns. The biological process of decomposition, which is mostly carried out by microorganisms such as bacteria and fungi, is controlled by several conditions, including temperature and soil moisture (Hasanuzzaman and Hossain, 2014; Awasthi et al., 2022). Usually decomposition rises exponentially with temperature; that is, it increases by a factor for each 10° rise in temperature. However, even under deep and heavy snow, leaf breakdown does happen slowly over the winter (Taylor and Jones, 1990; Bargali et al., 2015b & 2018). During the first phase, decomposition was quick due to the energy richness and ease of breakdown of these molecules. However, the second stage decomposition was substantially slower because of lignin, as it is made up of many large and complicated molecules. The mass loss curve that arises from this quick initial breakdown and a longer, slower decomposition phase resembles an exponential decay curve (Swift et al., 1981; Bargali et al., 2015a; Akoijam et al., 2025).

4.3. Relationship between percent weight loss, days elapsed and carbon release

Pearson's correlation showed (always lower than $p < 0.05$ and $p < 0.01$) a correlation between different variables. Present days elapsed showed a significant negative correlation with carbon (%), i.e., carbon content decreasing in litter with increasing days elapsed, whereas time elapsed showed a positive correlation with carbon release pattern and weight loss showed a significant positive correlation with carbon percentage for all the species (**Table 4**). The products of litterfall decomposition aid in the nutrient return to the soil and the formation of soil organic matter. The relationship between nutrient flow and storage is a characteristic of ecosystems (Sarkar et al., 2025). The accumulation of organic matter in an ecosystem is controlled by the interplay between litter deposition and decomposition (Singh et al., 2004). Nath and Das (2011) studied the homegarden of Dargakona village in district Cachar, Assam, in Northeast India.

Table 4. Pearson's correlation showing the relationship between weight loss (WL), days elapsed (DE) and carbon release pattern in five homegarden tree species.

Species						
		F. auriculata	***F. palmata***	***C. australis***	***G. optiva***	***F. hispida***
DE	vs. carbon%	−0.962**	−0.898**	−0.937**	−0.843*	−0.927
	vs. carbon release	0.955**	0.892**	0.925**	0.819*	0.978
WL	vs. carbon%	0.959**	0.801	0.944	0.901	0.642

Where, * = significant at 0.05 level (2-tailed), ** = significant at 0.01 level (2-tailed); DE = days elapsed; WL = weight loss

In the present study, a significant variation of carbon release pattern was observed between wet seasons (March to May). This fluctuation might be caused by the later stage of decomposition and the changes in climate and weather patterns (rainfall and temperature). Higher temperatures and ideal rainfall during the rainy season (March to May) accelerate decomposition and, as a result, release more C into the soil and environment.

It is well established that biotic and abiotic elements like temperature, microbial activity, soil moisture, and litter quality affect the litter decomposition and the pattern of nutrient release (Mungai and Motavalli, 2006; Hattenschwiler and Jorgensen, 2010). Additionally, Semwal (2006) and Anthwal (2006) identified the components listed above that account for variations in an area's structural composition, which in turn account for patterns of nutrient release and litter formation. A faster rate of decomposition and release of nutrients during the wet season is caused by the higher temperatures, more rainfall and increased microbial activity. Thus, it is concluded that the decomposition rate of organic matter on the soil surface and within the soil has been improved by tree foliage, thus rendering the system vulnerable to leakage of nutrients from the soil sub-system. The release of nutrients into the soil through the decomposition of homegarden tree residues is a crucial ecological activity that regulates nutrient recycling (Singh et al., 2021).

5. Conclusion

This study advances knowledge of the leaf litter decomposition pattern of five homegarden tree species of the Kumaun Himalaya. *F. hispida* was the fastest decomposing species, while *G. optiva* was the slowest decomposing species among the selected species. The relationship between percent weight loss and time elapsed showed a significant negative correlation in all the species. Climatic conditions and edaphic properties also affected the litter decomposition and carbon release. Homegarden tree species in Kumaun Himalaya decompose at comparatively fast rates; the carbon in the decaying litter is recycled within the soil quickly, boosting its fertility and ensuring adequate carbon cycling in homegarden agroforestry methods.

Author contributions: Data collection: V; Writing-original draft: V; Investigation: AF; Writing-review & editing: AF; Conceptualization: KB; SSB; Methodology: KB; Supervision: KB; SSB; Data curation: KB; Visulaization: SSB.

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Conflict of interest: The authors declare they have no competing interests.

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