SOIL MICROARTHROPODS, LITTER DECOMPOSTION AND NUTRIENT MINERALIZATION IN A SUB-TROPICAL ECOSYSTEM AT MOKOKCHUNG, NAGALAND.

by

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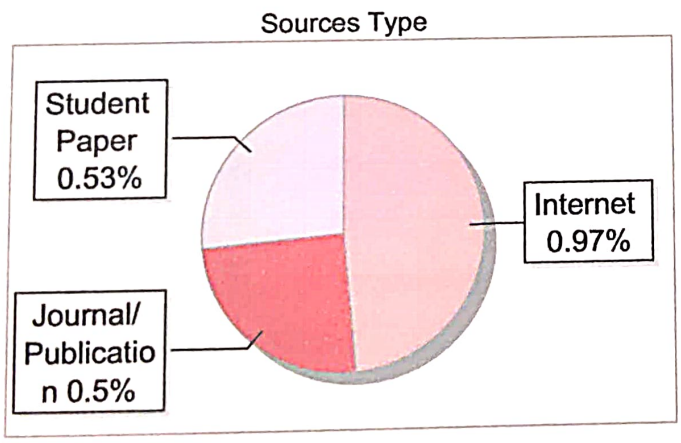

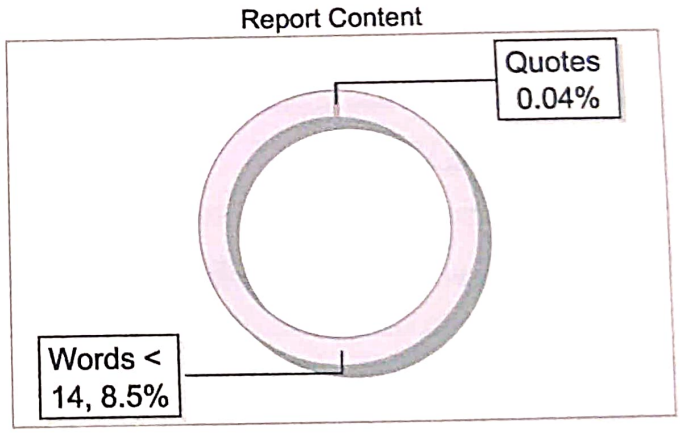

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LIST OF ABBREVATIONS

NF	:	Natural Forest
PF	:	Plantation Forest
MC	:	Moisture Content
ST	:	Soil Temperature
OC	:	Organic Carbon
N	:	Nitrogen
P	:	Phosphorus
K	:	Potassium
C:N	:	Carbon to Nitrogen
K	:	Decay constant
Av. N	:	Available Nitrogen
ANOVA	:	Analysis of Variance
TMS	:	Total microarthropods in Soil
TML	:	Total microarthropods in Litter

General Introduction

Litter decomposition

Leaf litter is a key driver of soil quality and plays a leading role in controlling nutrient availability for the plant and animal communities in terrestrial ecosystems. (Cotrufo et al., 2013, Hobbie, 2015; Porre et al., 2020). The addition of fresh litter enriches the soil with carbon and nutrients, supporting soil fauna and microorganisms which in turn accelerate microbial activity, facilitating the breakdown of organic matter and nutrient transport processes during early phase of decomposition (Hansson et al., 2010; Liao et al., 2016). Litter decomposition is a process of sequential breakdown and fragmentation of dead organic matter into successively finer particles until its structural integrity becomes indiscernible, ultimately resulting in the mineralization of organic molecules into their elemental constituents (Moore et. al., 2006; Castillo-Figueroa, 2024). This process is governed by litter quality, climatic conditions, and decomposer activity which regulates the carbon cycling between ecosystems and the atmosphere, influencing the global carbon budget and climate dynamics (Krishna and Mohan 2017; Joly et al., 2023). Parton et al., (2007) revealed that the climatic decomposition index encompassing both abiotic (climatic) and biotic (litter quality) drivers, was the most significant predictor of decomposition rates at a global scale, explaining 68% of the total variance ($R^2 = 0.68$). Among the abiotic factors, soil temperature and moisture are critical in altering the rates of organic matter decomposition and the mineralization of various organic materials (Onwuka and Mang, 2018; Petraglia et al., 2018). Soil temperature fluctuates both seasonally and diurnally due to variations in radiant energy and energy exchanges at the soil surface. For instance, an increase in soil temperature enhances nitrogen mineralization rates by stimulating microbial activity and accelerating the decomposition of organic matter (Lu and Xu, 2014). In addition, the chemical composition of litter especially the initial nitrogen content and the C/N ratio of leaf litter substantially affects decomposition rate (Gartner and Cardon, 2004; Du et al., 2020). Litter with higher nitrogen content decompose more rapidly (Quideau et al., 2005; Swarnalatha and Reddy, 2011; Upadhyaya et al., 2012). Litter with low lignin and high nitrogen content is generally considered high-quality material for decomposition (Osono and Takeda, 2004; Isaac and Nair, 2006; Zhang et al., 2008). Local macroclimatic factor further influence decomposition (Chen et al., 2018; Joly et al., 2023). The favorable temperature and moisture conditions during the rainy season facilitate rapid decomposition. This is

indicated to be optimum for microbial activity leading to decomposition (Tangjang et al., 2015; Wise and Lensing, 2019). On the other hand, the rapid mass loss during this period can be attributed to favorable conditions for fast-decomposing litter, including high soil moisture content, high relative humidity, and conducive atmospheric temperatures, all of which indirectly promote soil biological activity (Isaac and Nair, 2005). The microbial community facilitated through leaf break down and consumption by Soil-dwelling microarthropods promotes leaching. This leads to biochemical transformation within the ecosystem as it fosters the proliferation of microbial communities involved with the biochemical transformation (Dey et al., 2010). Bacteria, fungi, and detritivorous invertebrates are the principal drivers in breaking down complex organic material. Therefore, it is important to understand the relationships between litter characteristics, climatic variables, decomposer community to better understand the processes that drive litter decomposition dynamics within an ecosystem. (Mori et al., 2020). Leaf litter breakdown involves diverse array of organisms such as insects, bacteria and fungi. A process that takes place both on the surface of the soil and within soil matrix, involves a multitude of interactions and mechanisms chemically, physically and biological agents (Graça, 2001; Hasanuzzaman and Hossain, 2014). These process entails two simultaneous mechanisms (a) microorganisms decompose complex organic compounds like lignin and cellulose into minerals and humic substances, thereby enriching soil fertility, and (b) the percolation of soluble compounds into the soil initiates a complex sequence of biogeochemical transformations, in which the carbon, nitrogen, and various elemental constituents undergo a series of complicated processes resulting in their gradual mineralization (Sayer et al., 2020; Swart et al., 2020). A comprehensive overview of the variables that govern leaf litter decomposition is illustrated in **Fig. 1**. It schematizes, in a graphical way, the interplay between critical factors such as microbial activity, nutrient dynamics, and physical processes, including the breakdown of organic matter and changes in litter chemistry.

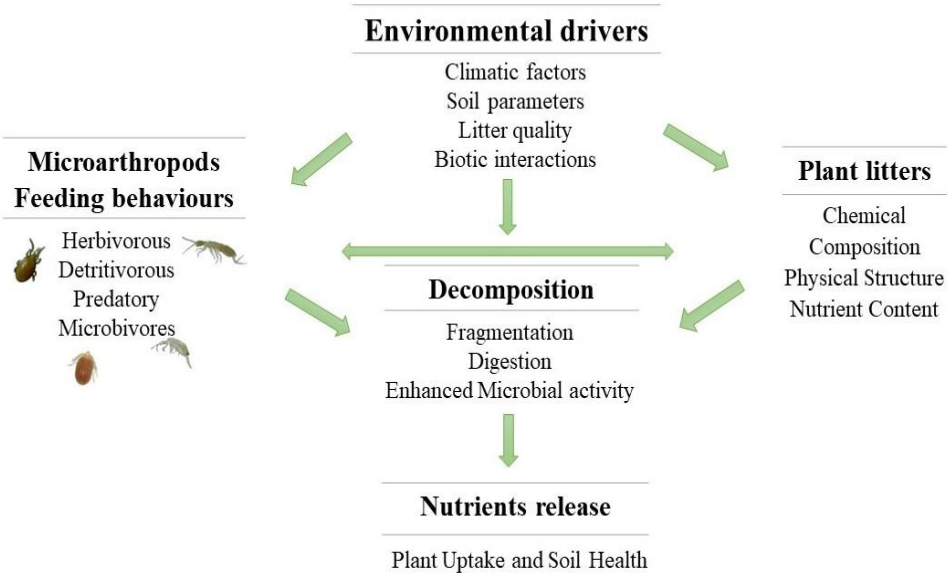


Fig. 1: **Variables governing the process of leaf litter decomposition.**

As shown in **Fig. 1**, key variables influencing leaf litter decomposition include climatic factors including temperature, precipitation and humidity would directly influence the rate and direction of decomposition rates by changing the microbial activity and enzymatic reactions. It was found that the addition of soil mesofauna had a major positive influence on the litter decomposition rates. In addition, this effect was stronger when considering better-quality litter materials than those of lower quality. These findings indicate that soil fauna affect mass loss either directly or indirectly (Song et al., 2020). The efficiency of this process is profoundly influenced by the diversity of plant species present. A biodiverse and rich plant community enhances nutrient cycling, which is, in turn, a more capable and longer-lasting way of promoting the sustainability and vitality of the forest ecosystem as a whole (Li et al., 2016; Osono, 2017). A large fraction of carbon is emitted through the respiration of decomposer organisms, and nutrients are freed into available forms due to mineralization (Krishna and Mohan 2017; Veen et al., 2019). The recycling of primary nutrients, released during the litter decomposition stage, begins within the soil ecosystem that primarily serves as a nutrient source for trees and plant growth. This phenomenon encompasses a range of micro and macro elements that are critical for the normal physiological development of both flora and fauna (Sayer et al., 2020). Thus, litter decomposition is an important ecological process in forest ecosystems as it serves to reintroduce essential components back into the environment (Leppert et al., 2017; Froufe et al., 2019; Cassart et al., 2020).

Soil microarthropods

Soil fauna, particularly soil microarthropods play an essential role in ecosystem function because they act as intermediaries in food chains, food webs, and nutrient cycling decomposers, functioning alongside other detritivores macroinvertebrates, They have dual effects in soil ecosystems in changing the composition and function of soil microbial communities by feeding on them while supporting larger fauna as food source and thus strutting soil biodiversity and ecosystem function (Briones, 2014). Although minute in size they play disproportionally large roles in maintaining soil quality (Lakshmi et al., 2020), increasing soil carbon content, and driving biogeochemical cycling within terrestrial ecosystems (Gergocs et al., 2022; Jernigan et al., 2024). The soil microarthropods community is taxonomically diverse, dominated by Acarines and Collembolas (Mandal et al., 2019) which constitute more than 90% of the microarthropod population. Complementing this majority, a plethora of other taxa, including proturans, pauropods, diplurans, dipteran larvae, small spiders, pseudoscorpions, as well as select homopterans, coleopterans, and thrips, contribute to the remaining minority, forming less than 10% of the microarthropod community (Wang et al., 2009; Sitlhou and Singh, 2019). Among these groups, oribatid mites (Oribatida, Acari) are particularly abundant and play an active role in organic matter decomposition and nutrient regulation (Krause et al., 2021). Similarly, collembola, a major detritivore, significantly influence litter decomposition, nutrient cycling, and plant growth by enhancing microbial activity (Verma and Paliwal, 2010; Bahrndorff et al., 2018; Neher and Barbercheck, 2019). Seasonal fluctuations in soil microarthropod populations are a common ecological pattern. Sarkar et al., (2016) observed that across different sampling sites, the seasonal dynamics of soil microarthropods followed a broadly similar trend, with Acarines consistently representing the most dominant group and collembolans ranking second in numerical abundance. Guo et al., (2022) also observed that the total abundance and diversity of soil microarthropods peaked in summer, with significantly lower values recorded in spring and autumn. In agreement, Sharma and Paewez, (2017) also reported significant seasonal variation in the overall densities of soil microarthropods, highlighting their sensitivity to environmental changes. This highlights the potential of soil microarthropods as consistent bioindicators for assessing the combined effects of land-use practices and seasonal dynamics on soil quality. Furthermore, in warm, humid environments, where plant litter decomposition rate is considerably fast, soil

microarthropods become more prominent in driving this critical ecological process (Wang et al., 2009). Overall, the evidence points to soil microarthropods as keystone components of terrestrial ecosystems, linking litter inputs with microbial activity and nutrient availability, thereby maintaining ecosystem functioning and productivity.

Role of soil microarthropods in litter decomposition and nutrient mineralisation

Microarthropods influence organic matter decomposition and nutrient cycling both directly, through its consumption, and indirectly, through grazing on microbial biomass (Soong and Nielsen, 2016). Their activity can enhance nutrient mineralization and plant growth responses. For instance, the reduction in microarthropod abundance resulted in slower litter decomposition, thereby limiting the transfer of carbon from litter into soil and microbial pools during the initial 18 months of the process (Soong et al., 2016). Similarly, Forey et al., (2015) demonstrated that Collembola, through their influence on both biotic factors (e.g., fungal biomass) and abiotic factors (e.g., nutrient availability), can modify plant morphology and chemistry, ultimately promoting flowering in *Poa annua*. Haque et al., 2024 also reported Collembola as key contributors to litter decomposition and nutrient cycling, facilitating the assembly of soil food webs in developing intertidal habitats. Their ability to persist under frequent inundations highlights their resilience, positioning them as important indicators of environmental filtering and essential drivers of salt marsh ecosystem functioning. Among the soil microarthropods, Mesostigmata are the primary predators in soil and litter (Salmane and Kontschan, 2005; Andrievskii et al., 2015;), while Prostigmata exhibit diverse feeding behaviors, including algivory, bacterivory, fungivory, phytophagy, predation, parasitism, and parasitoidism (Luxton, 1981). Springtails are generalist feeders that consume a wide range of resources, such as fungi, bacteria, mosses, spores, decaying plants, and organic debris (Sadaka-Laulin et al., 1998). In addition, Oribatid mites enhance litter mass loss, stimulate microbial respiration rates, and reduce fungal biomass (Hansen, 1999; Heneghan et al., 1999). Other microarthropod taxa encompass Isopoda, Myriapoda, and Insecta. Protura, Diplura, and Pauropoda are generally less abundant or infrequently encountered. Despite their lower abundance, these taxa contribute to the functional dynamics of the microarthropod community. The relative contribution of these biotic groups to decomposition processes varies with disturbance intensity and other environmental factors (Castro-Huerta et al., 2015; Kumar and Singh, 2016). Microarthropods facilitate the breakdown of detritus into smaller particles. As shown in **Fig. 2**, thereby

increasing the surface area available for microbial colonization and enhancing substrate moisture levels, which in turn stimulate microbial activity (Filser, 2002). They are considered to enhance decomposition indirectly, by fragmenting leaf litter and increasing the surface area available for microbial colonization, thus stimulating microbial activity in their faeces (David, 2014).

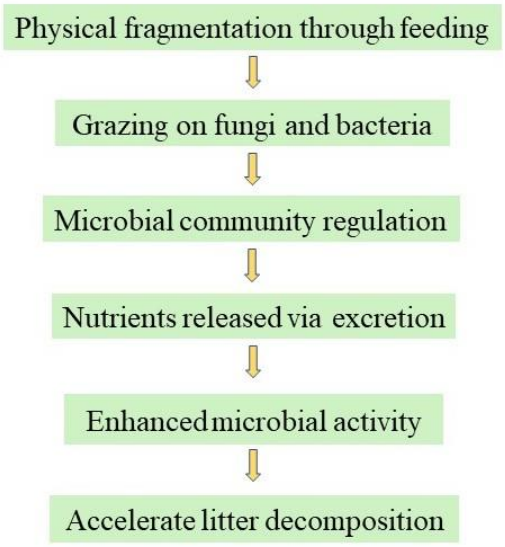


Fig. 2: Illustration of the influence of soil microarthropods on litter decomposition.

Microarthropods exert both direct and indirect influences on plant systems through their interactions within the soil environment and other biota. Indirectly, they modulate plant health by mediating soil organic matter decomposition, nutrient cycling, pathogen suppression, and plant-soil feedback mechanisms. These indirect effects collectively impact plant health, highlighting the pivotal role of microarthropods in shaping ecosystem dynamics and plant growth (Patoine et al., 2017; Neher and Barbercheck, 2019; Jernigan et al., 2022). Collembola, in particular, contribute to decomposition primarily through grazing on fungal hyphae (Coleman et al., 2004; Ngosong et al., 2014). Such direct interactions with fungal communities may have indirect effects on nutrient cycling (Moore et al., 1987). By modifying microbial community structure and activity, microarthropods indirectly enhance microbial processes through mechanisms such as litter fragmentation, dissemination of microorganisms, and grazing on fungi and bacteria (Ineson et al., 1982). Overall, microarthropods are crucial for ecosystem functioning**,** as they regulate the

transformation of decomposing litter into soil organic matter and influence soil carbon sequestration and ecosystem productivity**.**

Rationale, Scope, and Objectives

Global meta-analyses and experiments have demonstrated that soil microarthropods accelerate decomposition and nutrient mineralization by fragmenting litter, stimulating microbial activity, and facilitating nutrient turnover (Kampichler and Bruckner, 2009; Li et al., 2024). Their effects are especially pronounced in tropical and subtropical climates, where high temperature and rainfall create conditions for rapid organic matter turnover. In India, litter decomposition studies have been conducted in diverse forest and agroforestry systems, emphasizing the role of litter quality, seasonality, and abiotic drivers (Shanij et al., 2023; Arora et al., 2024; Singh et al., 2025). Regional research from Northeast India has also contributed insights. For example, Devi and Yadava, (2010) studied the Influence of climate and litter quality on litter decomposition and nutrient release in sub-tropical forest of Northeast India, while Walling et al., 2018 studied dynamics of litter carbon and nitrogen in forest fallows following shifting cultivation in Mizoram, Northeast India. More recently, studies from Nagaland revealed litterfall patterns and decomposition rates in subtropical riparian forests (Leishangthem and Singh, 2021) and compared decomposition dynamics between natural and plantation forests, finding seasonality to be the dominant driver of mass loss (Magh et al., 2024). Soil microarthropod diversity has also been assessed in Northeast India, with higher population densities and diversity observed in forest soils compared to plantations or degraded sites. For example, Das, (2021) reported greater abundance of Oribatida mites and Collembola in Tripura forest soils than in tea and rubber plantations, while studies from Assam documented significantly higher densities of soil Acarina in natural forests compared to disturbed ones (Borah and Kakati, 2014; Tsurho and Ao, 2014). These findings highlight the ecological sensitivity of soil microarthropods to vegetation type and land-use change. Despite these advances, there remains a critical knowledge gap: no study has explicitly examined the role of soil microarthropods in litter decomposition and nutrient mineralization in Nagaland's subtropical forests. With the state's growing shift toward monoculture plantations, understanding how microarthropods mediate decomposition and nutrient release in contrasting forest ecosystems is essential for sustainable forest management. The present study addresses this gap by focusing on the interaction between soil microarthropods, litter quality, and seasonal variation in

two adjacent forest types (Natural and Plantation forests) of Mokokchung, Nagaland. It seeks to generate novel insights into how microarthropods regulate decomposition dynamics and nutrient cycling under different ecological contexts. Specifically, the objectives are:

1. To document the soil physico-chemical properties and analyze the seasonal and annual rates of litter decomposition in the two forest types.
2. To assess the population density and diversity of soil microarthropods in litter and soil, and evaluate how these communities vary across seasons and forest types.
3. To determine the role of soil microarthropods in regulating decomposition and nutrient release patterns, and to examine how these effects are influenced by litter quality, seasonality, and forest type (natural vs plantation).

Biodiversity fluctuations can lead to alterations in ecosystem function, such as the decomposition of dead organic matter, which would, in turn, affect carbon cycling and nutrient recycling (Gessner et al., 2010; Cardinale et al., 2011). Correspondingly, the better our understanding of how these physical parameters modulate decomposition dynamics stands to enhance our capacity for more precise predictions regarding the potential ramifications of global warming on nutrient cycling and the overall resilience of ecosystems in the face of environmental change (Song et al., 2014). This is especially relevant in subtropical forest ecosystems, where high species richness and strong seasonality interact to shape decomposition pathways and nutrient turnover. Against this backdrop, the present research integrates ecological, climatic, and biological perspectives to examine the role of soil microarthropods in regulating nutrient cycling processes. By focusing on natural and plantation forests in Nagaland, this study addresses an important knowledge gap in understanding the functional significance of decomposer communities in Northeast India. The findings are expected to advance broader ecological understanding of subtropical forest dynamics while also offering a scientific foundation for promoting sustainable land-use practices, biodiversity conservation, and forest management strategies in the region.

Litter dynamics and soil microarthropods play a crucial role in assessing the stability and health of vegetation across the globe. Their interactions within the soil environment offer vital insights into ecosystem functioning, particularly in relation to plant growth and sustainability. Thus, the study of litter decomposition and soil microarthropods has become a critical focus in ecological research, attracting increasing attention from scientists worldwide. Over the years, a substantial body of work has explored litter decomposition processes, with particular emphasis on the population dynamics of soil and litter-dwelling microarthropods across diverse ecosystems. Researchers have examined both seasonal and spatial variations in these populations, as well as their sensitivity to changing edaphic (soil-related) and climatic conditions. This chapter highlights the most relevant studies pertaining to the present research, drawing on insights from both global literature and region-specific investigations, particularly those focused on India and the Northeastern region.

Litter decomposition (International status)

Litter decomposition is a key ecological process influenced by a range of biotic and abiotic factors, including litter quality, climate, microbial and faunal activity, and vegetation type. Numerous international studies have advanced our understanding of these dynamics through field experiments and meta-analyses. In a comparative study, Liu et al., (2005) found that litter from 10 dominant native tree species decomposed 1.36–3.06 times faster in tropical forests than in subtropical ones in southern China. Parsons et al., (2014) focused on seasonal patterns in a tropical rainforest and found that leaf litter decomposability was lower during the dry season due to higher phenolic concentrations and reduced moisture. Sohng et al., (2014) highlighted strong seasonal trends in a temperate forest, where most decomposition occurred during the summer, regardless of tree species. Their study underlined that seasonal variation had a stronger influence on decomposition rates than species identity. Portillo-Estrada et al., (2016) showed that decomposition constants (*k* values) were generally higher in warmer, wetter environments and were positively associated with the litter's specific leaf area. Similarly, He et al., (2019) found higher decomposition rates in mixed litter within *Masson pine* plantations when understory vegetation was intact, with shrub and herbaceous layers contributing significantly to the process. Cakır and Makineci, (2019) reported significantly lower decomposition rates in *Quercuspetraea*(pure stand) than *Fagus orientalis* (mixed stand) using medium-mesh litterbags, and

observed substantial variation in carbon and nitrogen levels depending on mesh size. Additionally, they found differences in microarthropod diversity, with Isotomidae and Mesostigmata more abundant in mixed stands. Furthermore, mixed litter decomposed more rapidly than single-species litter in subtropical areas. Liu et al., (2020) conducted two meta-analyses of 69 experiments, revealing a global synergistic effect: litter mixtures decomposed 3–5% faster than expected, particularly when low-quality litter was involved. Using the litter-bag method over one year. Bhattarai and Bhatta, (2020) studied the decomposition rates and nutrient mineralization patterns of five tropical tree species (*Shorearobusta, Ficushookeri, Mallotusphilippensis, Artocarpuslakoocha,* and *Dilleniapentagyna*) in Hetauda, Makawanpur, Nepal and found that *M. philippensis* exhibited the highest decomposition rate (73.49% weight loss; k = 0.33), while *S. robusta* had the lowest (54.01% weight loss; *k* = 0.18). Yang et al., (2022) analyzed the influence of climate and site-specific conditions in litter decomposition involving 5,040 litterbag samples. In a litter decomposition study along a climatic gradient in Europe, encompassing 110 tree species mixtures across 194 forest plots, Joly et al., (2023) observed that decomposition was primarily driven by litter quality, faunal activity and site-specific conditions and microclimates played a significant role in decomposition both directly and indirectly. Li et al., (2023) reported synergistic decomposition effects in mixed litter samples from Mount Tai, except when was included, which led to additive rather than synergistic effects. Their findings showed that bacterial communities were shaped by initial litter chemistry, particularly C, N, P content, and stoichiometric ratios such as C/N and lignin/N. In a related study, Zeng et al., (2023) found that mixed litter exhibited higher mass loss than single-species treatments, suggesting that mixed planting and nutrient-rich soils enhance decomposition and nutrient cycling. A global meta-analysis by Zeng et al., (2024), covering 476 case studies across 93 sites, found that invertebrates enhanced forest litter decomposition by 1.4 times more in tropical and subtropical regions compared to other climatic zones, reinforcing the ecological importance of faunal communities in *Robiniapseudoacacia* warmer biomes. Siebenhart et al., (2025) reported that litter decomposition across 116 dryland sites was more influenced by temperature, precipitation variability, and cloud cover than mean annual precipitation.

Litter decomposition (National status)

In India, research on litter decomposition has gained momentum in recent decades, with studies spanning various forest types, climatic zones, and ecological conditions. These studies collectively highlight the importance of climate, litter quality, vegetation type, and soil fauna in regulating decomposition processes. Devi and Singh, (2009) demonstrated that microclimatic variation affects litter decomposition directly and indirectly through changes in soil microarthropod populations. Their results showed a positive correlation between decomposition rates and both rainfall and moisture content, aligning with trends in arthropod abundance. Kumar et al., (2010) reported peak decomposition during the wet summer, with the lowest rates in the dry summer months. Rainfall had a stronger influence than temperature, and nitrogen and phosphorus concentrations in decomposing litter increased over time. Litter weight loss was significantly correlated ($P < 0.05$) with soil moisture and rainfall while studying the decomposition dynamics of *Shorearobusta*, *Madhucaindica*, *Diospyrosmelanoxylon*,and *Schleicheraoleosa*in a tropical dry forest in Barnawapara Wildlife Sanctuary, Bargali et al., (2015) showed the highest decomposition and nutrient release rates, particularly for nitrogen and phosphorus in *S. robusta*, while *M. indica* decomposed the slowest. Decomposition rates were positively correlated with rainfall, temperature, and humidity (except in *M. indica*), and litter mass remaining was inversely related to nitrogen and phosphorus content but positively correlated with potassium. Krishna and Mohan, (2017) provided a comprehensive review of decomposition processes in Indian tropical and temperate forests, emphasizing the influence of climatic variables such as temperature, rainfall, humidity, and seasonal shifts. In the humid tropics of Kerala, Madathil and Kodikunnath, (2018) investigated the decomposition of *Thyrsostachysoliveri* and found an exponential decay pattern with a decomposition rate constant of 0.009 day^{-1} and a half-life of 77 days. Ahirwal et al., (2021) compared tropical and subtropical forests in the Indian Himalayan region and reported higher annual litterfall and decomposition rates (*k*-values) in tropical forests. However, subtropical forests exhibited better litter quality.

Litter decomposition (Northeast India)

Barbhuiya et al., (2007) proposed a three-phase decay model in Northeast India, consisting of an initial slow decay phase, a rapid decomposition phase, and a final

slow decay stage. They observed that soil nitrogen and phosphorus levels, along with rainfall, temperature, and soil moisture, were positively correlated with decomposition rates. Pandey et al., (2007) highlighted the significant role of relative humidity and mean temperature in regulating mass loss rates, reporting greater nutrient conservation efficiency in natural forests than in plantations. Tripathi et al., (2009) reported that leaf litter made up 65-76% of total litterfall in the studied forest systems, with decomposition rates peaking during the rainy season and dropping significantly in winter. Devi and Singh, (2009) examined leaf litter decomposition in a subtropical forest ecosystem in Manipur and found that both litter breakdown and soil microarthropod populations were positively correlated with moisture content and rainfall. Similarly, Devi and Yadava, (2010) investigated the decomposition of different tree species and found that *Leucaenadealbata* exhibited the highest decomposition rate ($k = 0.54$), attributed to its high initial nitrogen and carbon content. In contrast, *Symplocoswallichii* decomposed more slowly ($k = 0.33$), due to higher lignin and cellulose content and lower nutrient concentrations. Nath and Das, (2011) explored litter dynamics in a homegarden system in Assam, focusing on three bamboo species-*Bambusacacharensis*, *B. vulgaris*, and *B. balcooa*. They found that leaf litter had higher nitrogen, phosphorus, and potassium content, while sheath litter was richer in carbon, ash-free mass, and cellulose. In Mizoram, Lalnunzira and Tripathi, (2018) reported marked seasonal variation in decomposition over a 450-day study, with rainfall explaining 74-90% of the variability in litter mass loss. Singh et al., (2021) found that tropical wet evergreen forests exhibited rapid litter turnover and nutrient cycling, with mass loss ranging from 10–51% after 5 weeks to 16–85% after 10 weeks of decomposition. Singh et al., (2022) studied the decomposition of *Melocannabaccifera* and found it proceeded more rapidly in natural forests than in controlled microcosms, with only 7% litter mass remaining in natural conditions compared to 13% in microcosms. Lalremsang et al., (2022) examined the decomposition and nutrient release dynamics of *Flemingiasemialata* leaf litter in Northeast India using litter bags. Their findings showed that high nitrogen concentration (2.38%), low C/N (21.53), and lignin/N (4.05) ratios, along with low lignin content, significantly enhanced decomposition. The reported decay constant (k) was 0.01 day^{-1} (3.65 $year^{-1}$), with half-life (t_{50}) and near-complete decomposition time

(t_{99}) values of 96.43 and 695.73 days, respectively. Positive correlations were observed between decomposition and rainfall (r = 0.42) and temperature (r = 0.39).

Microarthropods (International status)

Liiri et al., (2002) conducted a microcosm experiment in central Finland using coniferous forest soil and silver birch seedlings to examine the relationship between soil microarthropod species diversity and plant growth under disturbance. They found that primary production (biomass) and nitrogen uptake increased slightly with increasing microarthropod species richness, though this effect was limited to low-diversity systems. Building on this, Cole et al., (2005) reported that microarthropod densities increased with elevated soil fertility in a nutrient manipulation experiment, indicating that soil microarthropod communities are primarily regulated by bottom-up forces, where enhanced plant inputs provide increased food resources. Rumble and Gange, (2013) investigated soil microarthropod communities on extensive green roofs over a 14-month monitoring period, incorporating both abiotic (e.g., substrate moisture) and biotic (e.g., plant and mycorrhizal colonisation) variables. Their results showed that overall soil faunal diversity was low, with only 42 species/morphospecies recorded. Communities were dominated by Collembola (61%) and mites (38%), although other groups such as Chilopoda, Coleoptera, Hemiptera, Araneae, and larvae of Diptera, Lepidoptera, and Coleoptera were also present in smaller numbers. Subsequent field studies across different ecosystems expanded the understanding of microarthropod community patterns. Fujii and Takeda, (2017) recorded four dominant taxa-Oribatida, Collembola, Prostigmata, and Mesostigmata-that accounted for over 98% of the total abundance in a natural *Chamaecyparis obtusa* forest in Japan, with Oribatida being the most dominant, followed by Collembola (46,887 individuals from 22 taxa). Similarly, Çakır and Makineci, (2018) observed high mean annual abundances of soil microarthropods in Belgrad Forest, Istanbul, with 42,851 individuals m^{-2} in oak stands and 42,276 individuals m^{-2} in Scots pine plantations. Ojeda and Gasca-Pineda, (2019) also reported Acari as the most abundant and diverse group in the Cuatro Cienegas Basin, dominated by Prostigmata (20 families) and Oribatida (16 families). More recently, Gwiazdowicz et al., (2022) investigated King George Island (Antarctica) and found Collembola to be the most abundant group (10,285 individuals), followed by Acari (2,237 individuals). In the same year, Guo et al., (2022) examined soil microarthropods in the Urat Desert Steppe, Inner Mongolia,

reporting stable diversity across seasons with no significant differences, although abundance and species richness were significantly higher in summer compared to spring and autumn. Across the 844 individuals collected, 7 orders and 32 species were identified. Expanding further, Gbarakoro et al., (2023) found Oribatida to be the most abundant group (60%) in their survey, followed by Hymenoptera (16%), Mesostigmata (10%), Collembola (7%), Coleoptera (4%), Diplura (2%), and Isopoda (1%). Similarly, Gwiazdowicz et al., (2023) reported 310,508 specimens from King George Island, Antarctica, representing 17 species, including one Mesostigmata, nine Oribatida, and seven Collembola. The most recent contributions emphasize the influence of environmental factors and litter interactions. Chen et al., (2024) highlighted that seasonal fluctuations exerted a stronger influence on the structure and function of oribatid mite communities than tree diversity, underscoring the role of abiotic conditions and resource availability as primary drivers

Microarthropods (National)

In a study from wetlands and croplands of Indo-Gangetic plains of North Bihar, Lal et al., (2024) highlighted on land-use differences in community composition and population dynamics of Collembola and Acari. Akoijam and Bhattarcharyya, (2012) recorded seasonal variation of soil arthropod density ranging from 6635.70/m^2 (October) to 2211.90/m^2 (January) with a significant positive correlation with soil temperature and moisture. Among the groups identified, Colembolla and Acari were dominant. Abbas and Parwez, (2012) observed that Collembola were the most abundant group, with the highest density (13.54%) and abundance (19.70%), followed by Hymenopterans (14.83%) and Acari (13.22%), while Acari exhibited the highest absolute frequency (93.75%) in Aligarh district, Uttar Pradesh. In an extensive study on the seasonal diversity and species-specific differences of soil microarthropods in two different managed agroecosystems at Aligarh, Abbas and Parwez, (2012) emphasized the habitat quality as a key determinant of community structure. Sarkar et al., (2016) highlighted distinct variations in abundance and diversity of soil microarthropods across four different soil habitats from North Dinajpur, West Bengal. Bini et al., (2016) documented that microarthropod diversity indices, including evenness, richness, dominance, and abundance, reached their maximum during the monsoon and post-monsoon periods, whereas summer months consistently recorded the lowest values. In tropical home gardens of Kerala, Lakshmi and Joseph, (2016)

identified six dominant groups viz., Collembola, Coleoptera, Hymenoptera, Araneae, Acari, and Diplopoda, whose abundances varied seasonally, with maxima during the rainy season, highlighting the ecological role of diverse microarthropod assemblages in these managed landscapes. Abbas and Parwez, (2020) reported Collembola as the dominant group in vegetable agroecosystems, exhibiting a significant negative correlation with soil temperature and a positive correlation with nitrogen levels, they also observed that populations peaked in spring and winter following sharp decline during summer months. Dey and Hazra, (2021) recorded 44 species of soil microarthropods, underscoring their importance in nutrient cycling, ecosystem functioning, and as bioindicators of soil quality. Recent large-scale assessments have further emphasized the diversity of Indian soil arthropods. Deepika et al., (2023) documented a total of 1,914 soil arthropod species, representing significant diversity within the classes Arachnida, Insecta, and Crustacea. Within these, the families Paronellidae, Scarabaeidae, and Lycosidae recorded the highest individual species counts, particularly in agricultural ecosystems, suggesting that these landscapes harbor considerable and often underestimated biodiversity.

Microarthropods (Northeast India)

Research in Northeast India has highlighted the rich diversity and ecological significance of soil microarthropods across diverse ecosystems, including forests, agroecosystems, tea gardens, shifting cultivation areas, and plantations. Chitrapati and Singh, (2007) further reported that microarthropod density decreased with soil depth but reached a maximum during the monsoon season. Devi et al., (2011) further demonstrated that soil moisture and organic carbon were significantly correlated with Collembola abundance, showing strong seasonal fluctuations. Paul et al., (2011) observed higher density and diversity of Collembola in forest soils compared to agroecosystems in Shillong, with seasonal trends showing increases from spring to autumn, followed by declines in winter. Tsurho and Ao, (2014a) also demonstrated that jhum lands harbored lower species abundance, diversity, and stability of soil Acarina communities compared to natural forests, reflecting the impacts of shifting cultivation. Studies from Assam by Borah and Kakati, (2014) revealed that soil and litter-dwelling microarthropods peaked during the monsoon and declined in the post-monsoon period, consistent with seasonal moisture availability. In a comparative study from Mizoram, Zodinpuii et al., (2019) recorded 97 microarthropod taxa

belonging to five classes, with natural forests supporting 88 taxa compared to only 48 taxa in shifting cultivation sites. Roy et al., (2020) documented 40 species of oribatid mites from 19 families in tea soils of Assam, with populations peaking post-monsoon and reaching the lowest abundance in summer. Gadaily et al., (2020) recorded soil arthropods belonging to five classes, 31 families, and 37 genera, with Entognatha being the most abundant group, followed by diverse representatives of Collembola, Oribatida, Mesostigmata, Protura, Hymenoptera, and Coleoptera from agricultural and horticultural systems of Meghalaya's mid-hills. Bhagawati et al., (2020) identified five Collembola species from four families, with *Cyphoderus* sp. as the most abundant (44.29%). Their study reported higher density and diversity in summer, suggesting more stable habitats during this season. Extending this, Bhagawati et al., (2021) found Collembola to be more abundant in forest ecosystems than in disturbed vegetable and tea ecosystems of Assam, with organic carbon and moisture showing significant positive correlations with their populations across all seasons. Das, (2021) observed oribatid mites as the most dominant group across land-use types, followed by Collembola, with highest abundance in forests, intermediate in tea gardens, and lowest in rubber plantations. Pator and Ray, (2022) also reported Collembola dominance, with peak densities in July and lowest in September, and a strong positive association with soil organic carbon. Syed et al., (2023) demonstrated that soil temperature and available potassium showed significant positive correlations with microarthropod populations in Northeast Indian ecosystems. Most recently, Mandal et al., (2024) described a new species, *Tomocerussikkimensis* sp. from Gangtok, Sikkim, underscoring the taxonomic richness of the group in the region.

Impact of soil microarthropods on litter decomposition

The role of soil microarthropods in litter decomposition has long been recognized. Seastedt, (1984) demonstrated that across 15 studies lasting 9–30 months, microarthropods increased litter mass loss by an average of 23%, with their feeding expected to promote greater mineralization of nitrogen, phosphorus, and cations as litter ages. Rombke et al., (2006) later identified Collembola and Acari as key bioindicators due to their high abundance, diversity, and functional roles in catalyzing organic matter decomposition and regulating soil food webs, while Adejuyigbe et al., (2006) revealed that the inclusion of microarthropods significantly altered nutrient concentrations in different litter types at various decomposition stages. From the

Indian perspective, Dey et al., (2009) examined mangrove litter-inhabiting microarthropods along the Midnapore coast, West Bengal, and recorded 44 species dominated by Acarina (36.3%) and Collembola (27.2%), with populations showing seasonal fluctuations driven by physico-chemical conditions and litter decomposition ranging from 34% at three months to 70% at twelve months. Similarly, Devi and Singh, (2009) in Manipur reported that leaf litter disappearance and microarthropod abundance increased significantly during the monsoon months (June–October), coinciding with canopy closure, increased temperature, and rainfall, which protected the forest floor from rapid desiccation. Kampichler and Bruckner, (2009), through a meta-analysis of 40 years of litterbag studies, further concluded that microarthropods exert a moderate but significant effect on litter mass loss. Wickings and Grandy, (2011) showed that the oribatid mite *Scheloribates moestus* significantly altered litter chemistry during decomposition, with effects varying according to initial litter quality. Kumar and Singh, (2016) emphasized that diverse arthropod groups such as mites, collembolans, pseudoscorpions, centipedes, millipedes, symphylans, proturans, and coleopterans play a vital role in nutrient release and forest productivity in relatively undisturbed Indian ecosystems, while Gergocs and Hufnagel, (2016) reported that decomposition responses varied by litter type, being influenced by the origin of microarthropods in pine litter, density in oak litter, but showing no effect in black locust litter. Roy et al., (2017) documented the role of microarthropods in grassland and agroforestry ecosystems, where they facilitated litter decomposition, enhanced nutrient acquisition, and promoted nutrient cycling, thereby improving soil fertility and ecosystem functions. Qiu et al., (2019) found that meso- and microfauna increased *Acer mono* litter decomposition by 15% and accelerated manganese release by 59% in Changmai Mountain, while Neher and Barbercheck, (2019) broadened the perspective by showing that microarthropods influence soil and plant health both directly (by preying on pests or serving as alternate prey) and indirectly (by enhancing plant resistance and nutrient balance). Yang et al., (2020) demonstrated that isopods enhanced carbon and nitrogen release during decomposition, and Jernigan et al., (2022) emphasized that microarthropod–microbe interactions influence decomposition, nutrient cycling, and plant–pathogen dynamics, with effects modulated by community diversity. Xu et al., (2023) reported that macrofauna, mesofauna, and microfauna together contributed up to 29% of litter mass loss, with

their greatest impact during the first four months of decomposition, facilitating cellulose and lignin degradation and promoting nitrogen release in later stages, while Chen et al., (2023) found that soil arthropods boosted global non-leaf litter mass loss by 32.3%, with effects varying across climates and ecosystems. Liu et al., (2024), analyzing 1,706 observations from 260 studies, revealed that nitrogen addition and drought reduced decomposition rates, while phosphorus addition, warming, and precipitation enhanced them, with combined global change factors mostly interacting antagonistically. Burtis et al., (2024) similarly noted that the impact of soil fauna on decomposition depends on litter chemistry, species, forest type, and climate gradients, highlighting the complexity of their role. Mamabolo et al., (2024) demonstrated that litter mass loss was positively correlated with soil fauna richness in livestock-integrated fields and was significantly greater in coarse mesh litterbags that allowed fauna access compared to fine mesh bags, while Wang et al., (2024) observed that soil fauna-mediated litter mass loss was influenced by climate, soil type, litter traits, and decomposition stage, with leaf morphological traits (length, width, and area) and climatic factors (temperature and precipitation) serving as moderators. Finally, Kishore et al., (2024) reiterated that soil arthropods contribute to litter decomposition and nutrient cycling through both direct consumption and indirect processes, with collembolans, oribatids, myriapods, and isopods acting as secondary decomposers by conditioning litter for microbial breakdown and contributing to soil structure through fecal matter and aggregate formation. The findings highlight that mesofauna contribute more to decomposing recalcitrant (low-quality) litter than high-quality litter. From the literature survey, it is evident that litter decomposition and population dynamics of soil and litter-dwelling microarthropods in Nagaland are influenced by seasonal, edaphic, and climatic factors across ecosystems. Despite Northeast India's biodiversity and ecological significance, studies on litter dynamics and soil microarthropods in Nagaland are limited. This research emphasizes the need for comprehensive investigations to uncover the ecological roles of these organisms in different ecosystems, which are essential for understanding litter decomposition, nutrient cycling, and sustainable ecosystem management in this understudied region.

Location

The present study was conducted at a plantation forest (PF) of *Duabanga grandiflora* (Roxb. ex DC.) Walp. (26º21'28.3"N and 94º33'41.4"E), and undisturbed natural forest (NF) (26º21'38.6"N and 94º33'31.7"E) at altitude ranges from 1283-1674m above MSL in a contiguous sub-tropical hill forest ecosystem of Mokokchung district, Nagaland, India **(Plate no.1).**

Natural forest (NF)

The NF is an old-growth stand, estimated to be over 75 years old, and remains relatively undisturbed. It supports a high diversity of native flora, contributing to the structural complexity and ecological integrity of the forest. The dominant plant species of the NF include *Molineria capitulata* (Lour.) Herb., *Pavetta indica L., Itea macrophylla* Wall. ex Roxb., *Ficus hirta* Vahl., *Trema orientalis* (L.) Bl., *Musa flaviflora* Simmonds, *Percicaria wallichii* Greuter & Burdet, *Pilea trinervia* Wight, *Oplismenus hirtellus* (L.) P. Beauv., *Smilax* sp., *Chromolaena odorata* (L.) R. M. King & H. Rob., *Diplazium esculentum* (Retz.) Sw. *Dracaena* sp., *Robus molluccanus* L., *Chloranthus elatior* R. Br., *Hodgsonia macrocarpa* (Bl.) Cogn. (**Plate no.2a)**

Plantation forest (PF)

The PF is a managed stand of *Duabanga grandiflora*, (Roxb. ex DC.) Walp. approximately 25 years old. Trees in this site are planted at a regular spacing of about 7 feet apart, resulting in a relatively homogenous canopy and reduced understory diversity compared to the NF (**Plate no. 2b).**

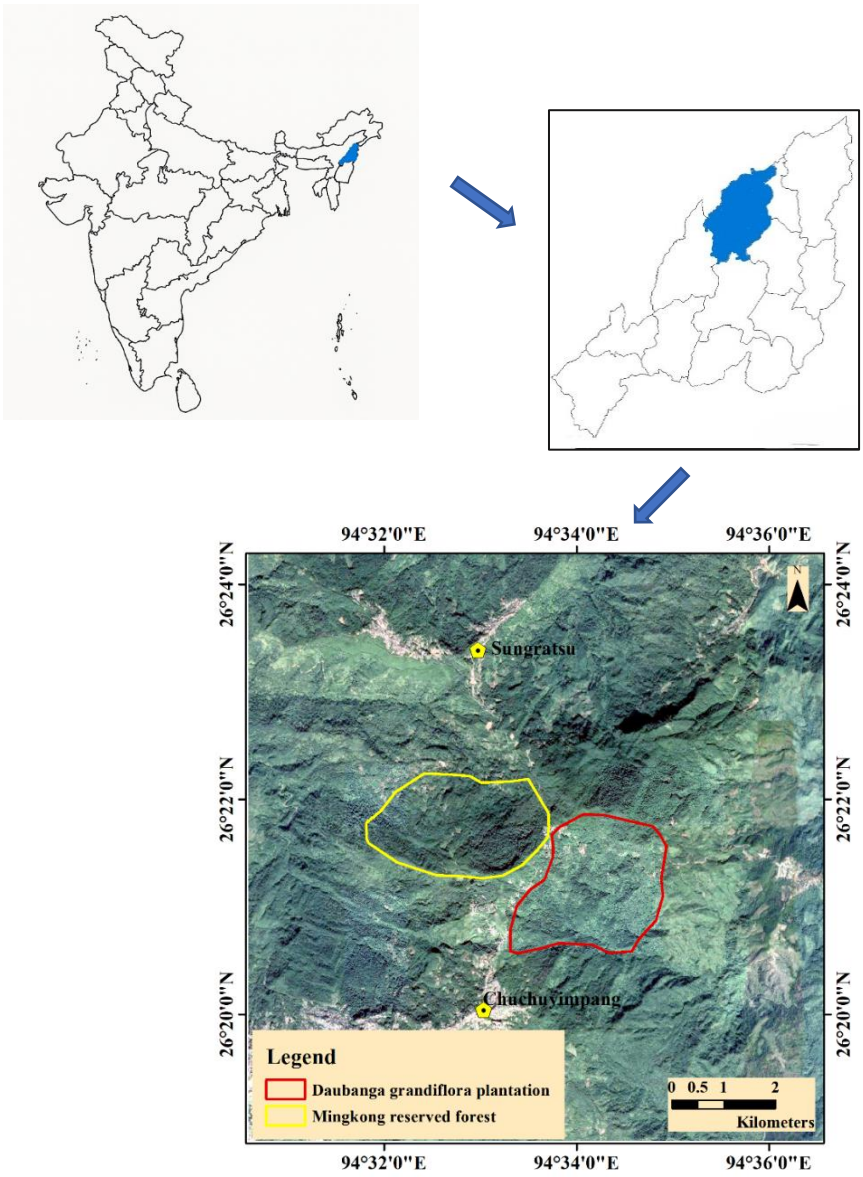


Plate no. 1. Map of the study area in Mokokchung district, Nagaland, India, highlighting the two study sites. The yellow outline delineates the Mingkong reserved forest (Natural forest), and the red outline marks the *Daubanga grandiflora* plantation (Plantation forest).

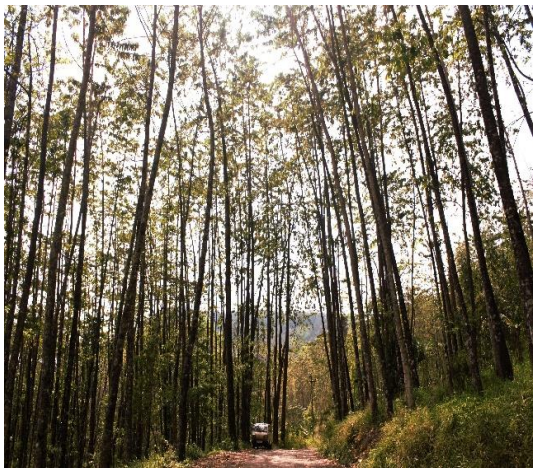


Plate no. 2a: Plantation Forest

Plate no.2b: Natural Forest

Climate

The study area experiences subtropical to warm temperate monsoon to cool dry winter with an annual mean rainfall of approximately 1942 mm. The climatic year can be broadly categorized into three distinct seasons:

- Pre-monsoon season (April to June).
- Monsoon season (July to October).
- Post monsoon season (November to March).

During the study period, the mean maximum and minimum air temperature varied from 14.65ºC (January) to 26.95ºC (August) and from 7.7°C (January) to 18.61°C (July) respectively. The mean relative humidity remained relatively high throughout the study period, ranging from 69.59% to 80.05%, with the highest values typically recorded during the month of May and July **(Fig. 3).**

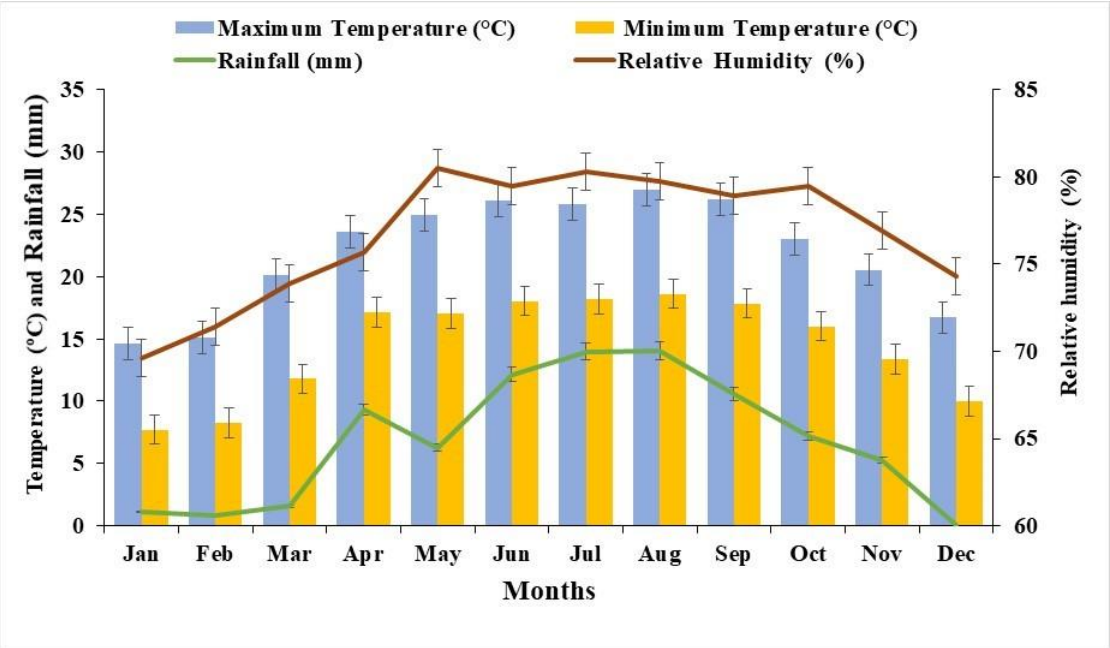


Fig. 3: Monthly (M*ean* ±SD) meteorological data during the two-year study period (April 2019-March 2021).

Experimental setup and design

The experiment was conducted over a span of two years, from April 2019 to March 2021. Each study site was divided in to 3 equal plots according to the elevation. A grid of 9 sub-plots, each measuring 25 m x 25 m were demarcated from the 3 plots (3 from one plot). These plots were organized in a 3-row by 3-column layout, and positioned 100 meters apart, as illustrated in **Fig. 4**. To quantify leaf litter decomposition rate and soil microarthropods, an in-situ experiment of litter bag technique (Crossley and Hogland, 1962) was employed throughout the 24-months duration. Freshly fallen leaves both from PF (*Duabanga grandiflora*) and NF sites were gathered during the height of the leaf litter fall month specifically during January and February 2019. Leaf litter of single species of *Duabanga grandiflora* were randomly collected from different sub plots of PF. In case of the NF site, leaf litters of major tree species representing different subplots were collected and mixed together almost in equal proportion to form composite litter sample. Sub-samples from leaf litter of each site (*Duabanga grandiflora* from PF and mixed litter sample from NF) were retained for the determination of initial chemical composition. The collected leaf litter from the designated sites was subjected to air drying at ambient room temperature. Subsequently, nylon litterbags with 15 cm × 15 cm (2 mm mesh size) were prepared and each of these bags was filled with 50g of leaf litter. Using 50*g* of litter in a 15x15 cm litter bag in lieu of the conventional practice of placing 10-20 g litter is primarily intended to secure a continuous and adequate supply of litter for the entire two-year study period. This modification is essential to maintain consistent experimental conditions allowing for more reliable and comprehensive data collection over the course of the study, thereby ensuring that there is a robust quantity of material available to support ongoing ecological processes and research objectives without interruption. In each of the study sites, 315 litter bags were placed on the forest floor (35 bags in each of the 9 sub plots) of the respective forest site at the end of the March, 2019. While only 216 litter bags were required to place in each of study sites (9 bags × 24 months), the additional 11 bags in each subplot were placed on the forest floor as reserves to compensate for any potential loss or damage during the research period.

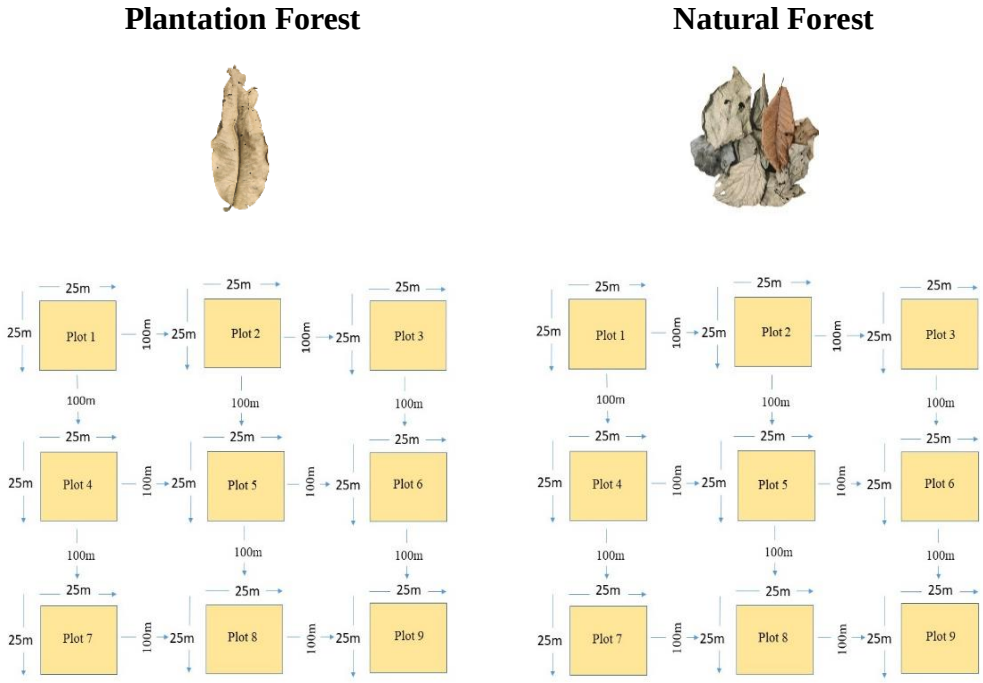


Fig. 4: Schematic layout of experimental plots and litter bag placement for a decomposition study. Single-species litter collected from the PF was placed in plantation plots, while mixed-species litter from the NF was placed in natural forest plots. This experimental design enables a comparison of decomposition and processes across different forest environments, highlighting the effects of species composition and site-specific factors.

Accordingly, 630 litter bags (315 bags for single species in PF and 315 bags for mix sample in NF) were kept in both sites (**Plate No. 3a)**. At designated intervals of 30, 60, 91, 121, 152, 182, 213, 244, 273, 305, 336, 364, 396, 426, 456, 487, 518, 549, 579, 609, 640, 671, 702, and 730 days of sample placement or post-incubation, 9 litter bags were retrieved at the monthly interval (specifically in the morning hours) from each site for extraction for litter microarthropods and decomposition studies (**Plate No. 3b)**.

Plate No. 3a

Plate No. 3b

Simultaneously, 9 sample of soils were excavated using soil corer with a diameter and height of 7.5cm from both the experimental sites to extract soil microarthropods, particularly within the designated region allocated for litter bag deployment. Both litter bags and soil samples were immediately packed in individually labelled polythene bags to avoid the loss of soil moisture, then they were brought to the laboratory for further extraction/analysis.

Extraction of soil and litter microarthropods

Microarthropods were extracted from the soil samples using Berlese-Tullgren funnels, following the modifications by Murphy (1962). A total of 32 samples (both litter and soil) were placed in the apparatus **(Plate no. 4a)** for 48 hours, with the exposure duration adjusted based on the moisture content of each sample. Both soil and litter microarthropods were extracted into collecting vial, containing 70% ethanol **(Plate no. 4b).**

Plate no. 4a

Plate no. 4b

Throughout the extraction process, the apparatus was regularly monitored to identify and repair faulty connections, as well as to replace fused bulbs when necessary. The extracted samples were carefully transferred into a Petri dishes, where microarthropod groups were separated using needles and a fine hairbrush. Sorting and screening were performed under a stereoscopic binocular microscope. Specimens with similar morphological features were grouped, and each group was segregated and preserved in vials containing 70% ethanol**.** After extraction, adhering soil and ingrown roots were removed from the litter bags, which were then carefully washed and oven-dried at 80°C to determine the remaining leaf litter weight. All soil microarthropods were identified up to the level of their order, family or species by using a range of taxonomic keys. The dominant microarthropod groups, Acarina (mites) and Collembola (springtails) were identified from the Acarology and Apterygota Section, Department in Zoological Survey of India (ZSI), Kolkata.

Physico-chemical analysis

Soil temperature was recorded in-situ using soil thermometer, soil moisture was determined by oven drying method (AOAC, 2000), and soil pH was measured using a digital pH meter at a 1:2.5 sample-water ratio. Organic carbon (OC) was determined by the wet oxidation method initially given by Walkley and Black (1934). Total Nitrogen was estimated following the digestion method given by Kjeldahl (1883) using Kel plus instrument (Pelican Equipment- Classic- DX VAT-E). Available soil phosphorus was determined by the Bray extraction method (Bray and Kurtz, 1945) using UV-Vis Lambda 355 spectrophotometer, and available soil potassium was determined by the ammonium acetate method given by Hanway and Heidel (1952) using SYSTRONICS 128 Flame Photometer. Total potassium and phosphorus for litter were determined by the tri-acid digestion method (Allen et al., 1974) using a UV-Vis Lambda 355 spectrophotometer. Lignin content was determined by the acid detergent fibre method (Van Soest, 1973).

Calculations for litter decomposition

The loss in mass of the litter (%ML) for each month was determined from the mass (M_1) of the remaining litter and initial litter mass values (M_0) using the formula (Olson, 1963).

$$\%ML = (M_0 - M_1 / M_0) \times 100$$

Decomposition constant *(k)* of leaf was estimated using the single exponential decay model.

$$\ln (M_0/M_1) = -kt$$

where 'M_0' is the initial mass of litter, 'M_1' is the mass of litter remaining after time t, 'ln' is the natural logarithm, 't' is the time (year) and *k* is the decomposition rate. The required time for 50% (t_{50}), 95% (t_{95}) and 99% (t_{99}) decay was calculated as

$t_{50}=0.693/k$, $t_{95}=3/k$ and $t_{99}= 5/k$ (Olson, 1963).

Percent of nutrients remaining in the undecomposed litter at time '*t*' was computed using the formula (Bockheim et al., 1991).

$$(C/C_0)\times(L/L_0) \times 100$$

Where, C is the nutrient concentration in the litter samples at the time of sampling. C_0 is the nutrient concentration of the initial litter; L is the mass of dry matter at the time of sampling and L_0 is the initial dry mass of the litter sample.

Statistical and community analysis

Statistical analyses in this study included correlation analysis, multiple regression analysis, analysis of variance (ANOVA), and Tukey's test, along with the calculation of mean and standard error. These analyses were performed using SPSS (Version 25.0), ORIGIN, and GraphPad Prism 5 statistical software.

Shannon-Weiner Diversity index

$$H' = -\sum_{i=1}^{s} Pi \text{ Log } Pi$$

Where, H' = Measure of Shannon and Wiener diversity

S = Total number of species in a sample

P_i = Proportion of the total number of individuals occurring in species i.

Margalef's Index

$$DMg = \frac{S-1}{\ln(N)}$$

Where, DMg = Margalef's Index

S = Number of species

N = Total number of individuals

H max'

$$Hmax' = \ln(S)$$

Where, S = Number of species

Evenness

$$H / H\ max'$$

Where, H' = Shannon-Weiner function or Mac-Arthur index of diversity

Average faunal resemblance

$$= \frac{C(S_1 + S_2)}{2 \times S_1 \times S_2} \times 100$$

Where, C = Number of species common to both the communities

S_1 = Total number of species in community 1 (NF)

S_2 = Total number of species in community 2 (PF)

Soil physicochemical dynamics in the study sites

The physicochemical properties of soil, including soil temperature (ST), pH, moisture content (MC), organic carbon (OC), nitrogen (N), phosphorus (P), and potassium (K), were systematically analyzed on a monthly basis over two years in both NF and PF.

Soil temperature

The monthly variations in soil temperature for both NF and PF (**Figure 5A**) shows a distinct trend was observed, with temperatures gradually increasing from May to September, reaching their peak in July. In PF, soil temperature fluctuated between a minimum of 16.73°C in January and a maximum of 23.57°C in July. Similarly, in NF, the lowest recorded soil temperature was 14.27°C in January, while the highest was 23.23°C in July. Lemla et al., (2025) reported that soil temperature is strongly governed by seasonal variation, rising to 33.92 °C in summer and falling to 22.04 °C in winter. In comparison, Temjen et al., (2021) observed soil temperature ranging from 17.83 ± 0.62 °C to 26.1 ± 0.08 °C, further confirming the pronounced influence of seasonal shifts on soil thermal regimes.

Soil pH

The soil pH levels across both study sites exhibited an acidic to slightly acidic nature, with values ranging from 3he soil pH values in the plantation forest (PF) and natural forest (NF) ranged from slightly acidic to moderately acidic, with PF showing greater variation (3.62–5.83) compared to NF (4.14–5.76) (**Fig. 5B**). Overall, PF soils were more fluctuating, while NF soils remained relatively stable, suggesting stronger buffering capacity in the natural forest. Comparable observations have been made in other studies. For example, Temjen et al., (2021) reported soil pH ranging from 5.94 ± 0.24 to 6.53 ± 0.02 in fallow land. Similarly, Imtimongla et al., (2024) observed that across different land uses, soil pH varied between 4.30–5.20 at lower altitudes (<200 m) and 4.40–5.29 at higher altitudes (>300 m). In line with these findings, Borkotoki and Goswami, (2024) noted that strongly acidic (pH 5.1–5.5) and medium acidic (pH 5.6–6.0) soils were predominant in the Lakhimpur district of Assam.

Soil Organic carbon

In PF, minimum soil OC was recorded in the month of March (2.1%) and July recorded maximum (3.7 %) (**Fig. 5C**). In NF, the minimum OC was recorded in the month of January (2.45%) and maximum in the month of July (4.04%). Sahoo et al.,

(2019) also observed the highest total organic carbon in natural forests (2.75%) compared to the lowest in grasslands (1.31%). More broadly, Shen et al., (2024) found that natural forests hold about 22.3% more soil organic carbon (SOC) than plantations, with environmental factors being the primary drivers of SOC variability in natural systems, whereas human management exerts a stronger influence in plantations.

Soil moisture

Throughout the study period, the total soil MC in the NF remained consistently higher than that in the PF (**Fig. 5D**). This difference in soil moisture levels may be attributed to the greater canopy cover and litter accumulation cover in NF. In NF, MC ranges from a minimum of 33.48% in January to a peak of 67.27% in August. In contrast, PF exhibited lower moisture levels, with values fluctuating between 31.24% in January and a maximum of 58.15% in April. Similar patterns have been reported in earlier studies, with Temjen et al., (2021) recording soil moisture values between 35.44 ± 1.09% and 53.39 ± 0.84%, and Nemhoihkim et al., (2025) reporting a range of 17.44 ± 0.52% to 44.13 ± 0.48%.

Available nitrogen

The available nitrogen (Av. N) exhibited variations across different months in both study sites, with NF showing higher concentrations (327.28 $kgha^{-1}$) in February to 545.84 $kgha^{-1}$ in September) as compared to PF (305.95 $kgha^{-1}$) in February to 461.82 $kgha^{-1}$) in August (**Fig. 6E)**. Comparable findings have been documented in earlier studies: Temjen et al., (2021) reported available nitrogen levels between 324.16 ± 8.42 and 443.20 ± 1.06 kg ha^{-1} in Mokokchung. Borkotoki and Goswami, (2024) observed a broader range of 37.33 to 687.76 kg ha^{-1}, and Mishra and Francaviglia, (2021) highlighted regional variability, with the highest available N (356.4 mg kg^{-1}) recorded in Mon compared to Zunheboto. Chase and Singh, (2014) also reported highest amount of nitrogen in natural foest. The order of availability of nitrogen was: natural forest (202.55) > Jhum fallow (159.49) > paddy field (47.34); which was significantly different among the three land use type at $p<0.05$.

Available phosphorus

Phosphorus availability in PF varied from 23.17 $kgha^{-1}$ (February) to 38.26 $kgha^{-1}$ (July), while in NF, it ranged from 27.59 $kgha^{-1}$ (April) to 47.35 $kgha^{-1}$ (September) **(Fig. 6F).** Similar trends have been reported in earlier studies, with Dandwate, (2020) recording available phosphorus values between 15.11 and 54.13 kg

ha^{-1} in Ahmednagar, and Mohanty et al., (2023) reporting phosphorus levels ranging from 23 to 33 kg ha^{-1} under the Zabo farming system of Nagaland.

Soil potassium

Soil K content did not show any definite increasing or decreasing trend throughout the study period **(Fig. 6G).** K in PF exhibited a range between 143.52 $kgha^{-1}$ (March) and 241.23 $kgha^{-1}$ (July), while in NF the values varied from 142.68 $kgha^{-1}$ (March) to 268.94 $kgha^{-1}$ (October). Comparable observations have been made in other studies: Mohanty et al., (2023) reported K availability of 255–285 kg ha^{-1} under the Zabo Farming System of Nagaland, while Pucho et al., (2023) documented values ranging from 190 to 213 kg ha^{-1} across different land-use systems in Khonoma.

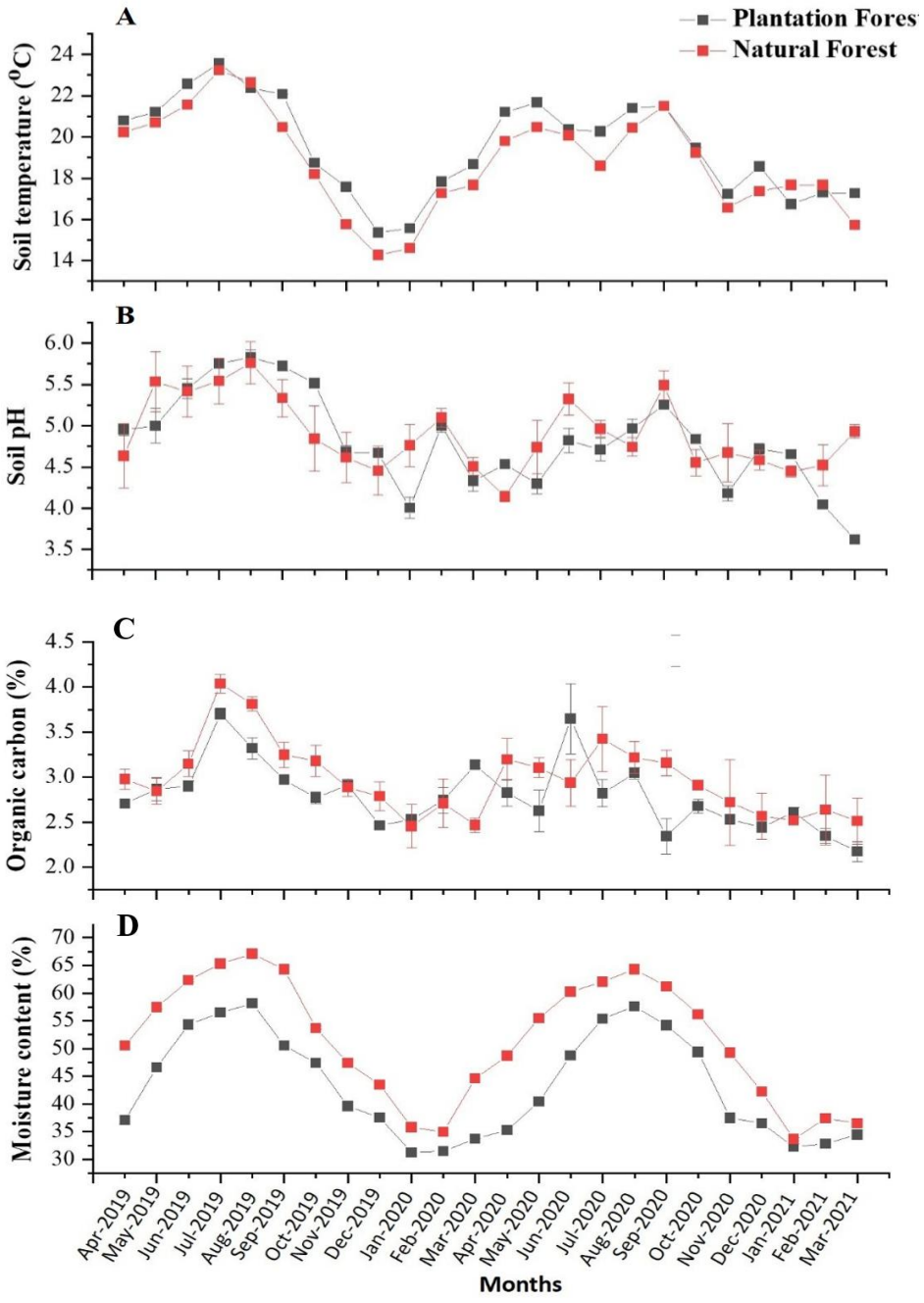


Fig. 5: Monthly variations in soil temperature, pH, organic carbon, moisture content over two years at both study sites.

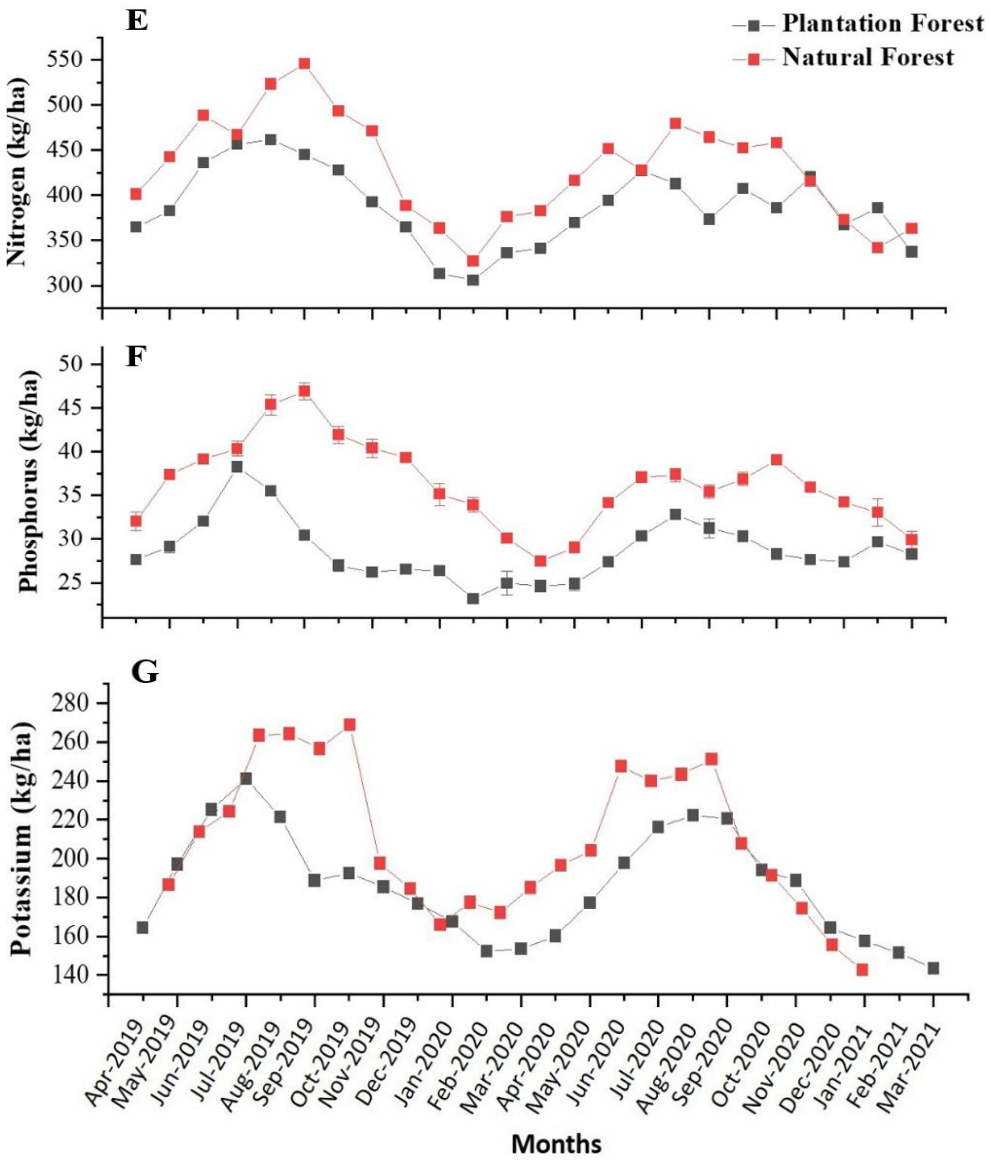


Fig. 6: Monthly variations in soil nitrogen, phosphorus and potassium over two years at both study sites.

Seasonal fluctuations in soil parameters over a two-year period

Across both study sites, soil pH is lowest during the post monsoon season and highest during the monsoon season. In PF, slight seasonal variations in pH were observed, whereas in NF, no significant seasonal differences were detected in the second year. Soil moisture follows a similar pattern, with the lowest levels recorded in the post monsoon season and the highest during the monsoon season. NF consistently maintains higher moisture levels than PF across all seasons. Organic carbon does not exhibit significant seasonal variation in PF, whereas in NF, significant seasonal differences were observed. Soil temperature is highest during the pre-

monsoon and monsoon seasons and lowest in the post monsoon season, with a significant difference between the pre-monsoon and post monsoon seasons at both study sites. Nitrogen concentrations peak during the monsoon season and are lowest in the post monsoon season. NF consistently exhibits higher nitrogen levels than PF, with significant seasonal differences. Phosphorus follows a similar seasonal trend to nitrogen, with the highest values recorded during the monsoon season. NF generally has higher phosphorus concentrations than PF. Potassium exhibits a pronounced seasonal increase, peaking during the monsoon season, with significant seasonal differences observed in both PF and NF **(Table 1).** Soil nutrient availability and dynamics are strongly influenced by both land use and seasonal variation. Soil nutrient availability and dynamics are strongly influenced by both land use and seasonal variation. Onweremadu, (2007) reported significantly higher amounts of soil nutrients under uncultivated lands such as grassland, woodland, and shrubland compared to cultivated systems. Similarly, Maqbool et al., (2017) observed that forests contain significantly higher available nitrogen than agricultural lands, largely due to greater organic matter inputs and higher nitrogen turnover during decomposition. They also reported higher levels of available phosphorus and potassium in forest soils relative to agricultural soils. Coppolino et al., (2022) highlighted that soil phosphorus availability varies seasonally, driven by shifts in mineralization–immobilization balances, plant uptake, and hydrological transfers. In support, Bini et al., (2013) found that available phosphorus was higher during the pre-monsoon compared to the post-monsoon and monsoon seasons in agricultural lands. Seasonal influences on potassium are also evident, with Mohapatra et al., (2025) noting greater depletion of exchangeable K during dry seasons. Nitrogen dynamics follow similar trends: Chen et al., (2023) reported that gross and net mineralization rates are generally highest under warm, moist conditions (often summer) and lowest during cold or dry periods. Sun et al., (2023) further demonstrated significant seasonal and spatial variation in soil biochemical properties, with nutrient pools and microbial enzyme activities peaking during warm and wet seasons. Soil pH also exhibits seasonal differences; Sarkar et al., (2024) recorded the highest pH in summer under Simarouba- and Kadamb-based tree plantations, while Sahu et al., (2016) reported maximum pH under forestlands and the lowest under rice fields.

Table 1: Chemical composition of soil in two study sites (Mean±SD, n=3). Different lower-case letters indicate significant differences according to one-way ANOVA.

Study site	Year	Season	pH	Moisture (%)	OC (%)	Soil temp (°C)	N (kgha^{-1})	P (kgha^{-1})	K (kgha^{-1})
PF	I year	Post monsoon	4.54±0.38^{c}	34.71±3.73^{c}	2.76±0.28^{a}	16.17±1.46^{b}	342.72±36.21^{c}	25.44±1.41^{c}	167.13±14.50^{c}
		Pre-Monsoon	5.13±0.27^{b}	46.00±8.66^{b}	2.82±0.10^{a}	21.44±0.93^{a}	394.54±37.28^{b}	29.61±2.24^{b}	186.81±30.49^{b}
		Monsoon	5.71±0.13^{a}	53.14±5.03^{a}	3.19±0.41^{a}	21.40±2.07^{a}	447.76±15.01^{a}	32.80±5.07^{a}	210.96±24.87^{a}
	II year	Post monsoon	4.24±0.45^{b}	34.69±2.26^{c}	2.68±0.17^{a}	17.91±0.68^{b}	379.47±30.29^{c}	28.26±0.89^{c}	161.08±17.25^{c}
		Pre-Monsoon	4.55±0.26^{ab}	41.48±6.80^{b}	3.65±0.54^{a}	21.02±0.66^{a}	368.47±26.62^{b}	25.62±1.53^{b}	178.38±18.77^{b}
		Monsoon	4.94±0.23^{a}	54.14±3.49^{a}	2.88±0.29^{a}	20.79±0.97^{a}	405.16±22.77^{a}	31.19±1.16^{a}	213.39±13.03^{a}
NF	I year	Post monsoon	4.69±0.26^{b}	41.15±5.62^{c}	2.66±0.19^{c}	15.91±1.53^{b}	385.30±53.23^{c}	36.02±4.26^{c}	179.61±12.15^{c}
		Pre-Monsoon	5.19±0.49^{a}	56.85±5.99^{b}	2.99±0.15^{b}	20.83±0.68^{a}	443.80±43.52^{b}	36.45±3.78^{bc}	208.21±19.57^{b}
		Monsoon	5.37±0.39^{a}	62.74±6.12^{a}	3.57±0.42^{a}	21.13±2.29^{a}	507.34±34.50^{a}	44.01±3.09^{a}	263.36±5.03^{a}
	II year	Post monsoon	4.63±0.19^{a}	39.68±6.17^{c}	2.59±0.09^{b}	17.00±0.84^{b}	390.43±46.47^{c}	34.66±3.43^{ab}	174.30±26.28^{c}
		Pre-Monsoon	4.74±0.59^{a}	54.86±5.89^{b}	3.08±0.13^{a}	20.11±0.34^{a}	416.81±34.48^{b}	30.37±3.54^{b}	195.32±9.58^{b}
		Monsoon	4.94±0.40^{a}	61.06±3.48^{a}	3.18±0.21^{a}	19.94±1.29^{a}	455.93±21.86^{a}	36.94±0.87^{a}	245.52±4.90^{a}

Litterfall is a major component of the nutrient cycle involved in regulating the accumulation of soil organic matter (SOM), nutrients intake and output, and other ecosystem services (Giweta, 2020). The amount and kind of litterfall affects the soil's physical, chemical, and biological characteristics, which in turn affects the soil formation and fertility and, consequently, the growth of trees (Chakravarty et al., 2019). Environmental conditions, soil property, litter substrate quality and decomposer communities are the major factors that leads to alteration of changes in the litter decomposition process (Yu et al., 2020; Rawat et al., 2021). Quite a few reports are available on the pattern of litter decomposition during growing season or over a gradient of ambient temperatures, as well as effect of microbial community upon decomposition of different litter types (Yu et al., 2020). Variations in temperature and soil moisture has also been reported to significantly influence the decomposition and nutrient mineralization processes in tropical and sub-tropical forests (Paudel et al., 2015), as well as semi-arid grassland environment (Wang et al., 2020). Plant species characteristics such as high specific leaf area, nitrogen and phosphorus content are associated with faster decay; while, high leaf dry matter content, lignin content, and secondary metabolites of plants are related to lower litter decay rate (Lin et al., 2019). However, plant functional traits might have an indirect effect on the rate at which litter decomposes through their impact on decomposer communities.

Gessner et al., (2010) and Reiss et al., (2009) noted that there are several trophic levels where biological diversity directly affects the decomposition of litter. This diversity includes plants that produce litter mixtures of varying quality, microbial decomposers and invertebrate consumers of different body size. Thus, litter diversity improves decomposability by providing decomposers with a wider variety of substrates, and this decomposability is often determined by the litter's chemical composition and structural characteristics, ultimately influencing soil organic matter accumulation and the duration of the decomposition process (Santo et al., 2009). In two different studies, Taylor et al., (1989) and Talbot et al., (2012) reported higher decay rates with litter that contained high nitrogen (N) concentration or low carbon/nitrogen (C/N) ratio and low lignin content or lignin/N ratio. Combining leaf litter from different plant functional types is found to accelerate the dynamics of C and N, as evidenced by the overall net positive impacts on

C and N loss i.e., higher C and N loss with further functional diversity (Handa et al., 2014). In species-rich forests, litter composition and decomposition are likely to be influenced by the spatial arrangement of tree species in the plot (i.e., tree planting pattern). Beugnon et al., (2023), reported that the diversity of tree species led to higher litter diversity and recorded 200 percent more litterfall in an area of mixed forest with eight species instead of monocultures.

Seasonality of litterfall and seasonal patterns of litter decompositions significantly influence the overall recycling of nutrients and soil fertility among different forest ecosystems. A noticeable decrease in litter mass is observed over the winter in cold temperate forests and other northern habitats, while it is seen in coniferous and broad-leaved forests during the spring season. The reason behind rapid litter decomposition rates during winter could be fungi, as they can develop at low temperatures and are crucial to the breakdown of litter in the winter. The wintertime freeze-thaw cycles may also contribute to the enhanced mineralization of C and N through physicochemical and/or biological impacts (Wang et al., 2013). With the seasonal fluctuation of soil temperature and moisture in local scales, litter decomposition rate differs from regional to global scale. A substantial correlation between seasonal rainfall and ambient temperature and litterfall productivity is noticed (Seta et al., 2018), as heavy rainfall at certain times of the year can lead non-senescent as well as senescent leaves to shed, that has a dual effect on the amount of litter production (Lu and Liu, 2012). However, during the dry season, decomposition is usually inhibited producing a temporary increase in the accumulation of leaf material and woody debris on the forest floor, and it resumes soon after the first rains (Schilling et al., 2015). Decomposition rates, seasonal climatic variation, the effects of seasonal fluctuations in litter properties, and the decomposition phase are thus intricately intertwined. Therefore, even though it is mostly determined by the local climate, the decomposition rate in any given ecosystem will differ based on the climate and precipitation patterns, type and quality of litter present, diversity of decomposer organisms, and the degree of habitat degradation (Cowan and Anderson, 2019).

The ongoing anthropogenic alteration of land use patterns necessitates an understanding of how variations in species diversity and composition impact the various ecosystem processes. Of particular importance is the rate of decomposition, which

controls the release of carbon and nutrients into the soil and is a crucial process in terrestrial ecosystems. Understanding the variations in decomposition rates across different litter types, biomes, and climatic regions is becoming increasingly important. This knowledge enables how decomposition could be affected by changes in biodiversity compared to the predicted decomposition changes brought about by climate change over the next 50 years (Mori et al., 2020). However, except for a preliminary investigation on litterfall production and rate of leaf litter decomposition in three dominant tree species in a subtropical semi-evergreen riparian forest (Leishangthem and Singh, 2021), there is a conspicuous lack of research on litter decomposition within the forest ecosystem in Nagaland. Thus, considering the period of global environmental changes, it is imperative to include the underappreciated functions of biodiversity when assessing future changes in the biogeochemical cycles and climate feedback. In the present study, we aim to investigate the seasonal variation of litter decomposition in two years in two different forest types, i.e., plantation and natural forest in the sub-tropical forest ecosystem. We also aim to examine and contrast whether leaf litter diversity has independent effects on plant litter decomposition and associated processes and variables (especially the nutrient dynamics) between the two different forest types. We hypothesize that mixed litter species increase litter decomposition and that litter decomposition is driven by different environmental conditions. We also hypothesize that litter diversity and nutrient availability increase litter decomposability.

Litter mass loss and decay constant

Litter mass in the litter bags remained stable (≈2%) during the first two months in the PF, after which there was a rapid increase in decomposition in the month of June and reached its highest during the monsoon season **(Fig. 7).** The initial phase of leaf litter decomposition exhibited rapid degradation, with the highest rates occurring during the monsoon season in both forest types. The reduction in mass during the initial phases of decomposition may be attributed to the presence of easily degradable compounds and tissues in fresh litter which is leached easily by rainfall or could be decomposed by microbes (Berg, 2000). These results are consistent with other studies indicating that climate change exerts both direct and indirect effects on decomposition dynamics, and rainfall and temperature, in particular, have been found to have a significant positive

correlation with the rate of leaf litter decomposition (Tan et al., 2020; Verma et al., 2021; Shad et al., 2023). The highest mass loss of 9.06% in NF and 7.92% in PF was observed in the month of August and October respectively. The half-stage of decomposition (0-50% mass loss) lasted for 273 days in the PF, while in the NF, it lasted about 244 days. Mixed leaf litter in NF experienced a 99.94% loss after 730 days, while in PF, the loss was 97.80% at the end of the decomposition (i.e. after 24 months).

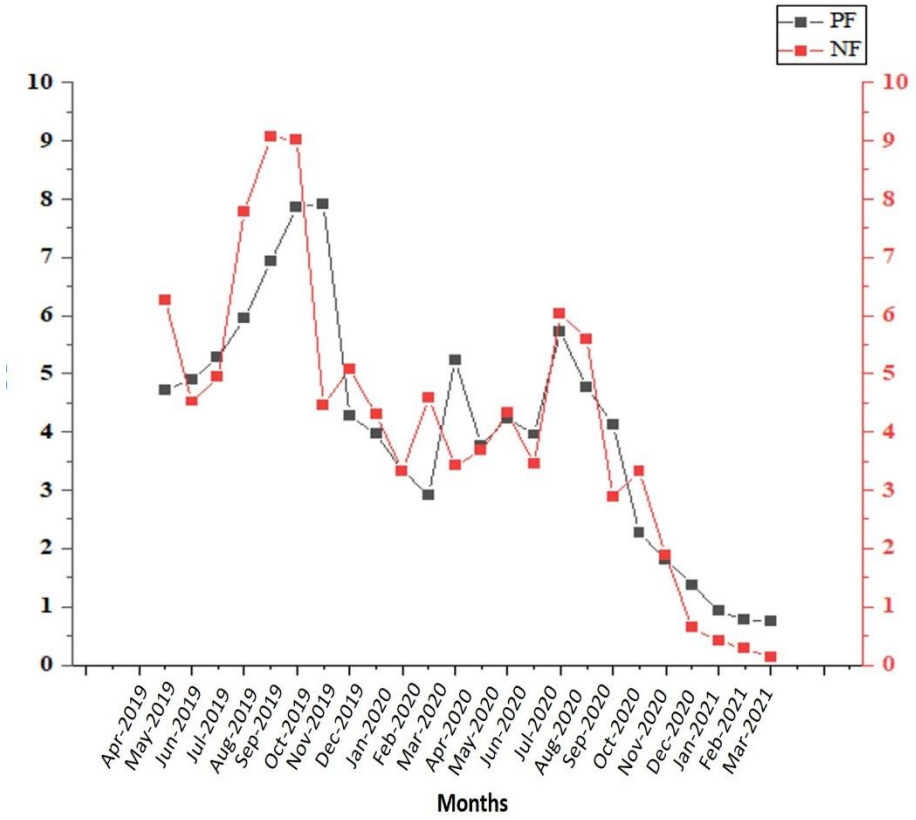


Fig. 7: Monthly litter mass loss (%) over a two-year period in both the plantation and natural forest.

The two-way ANOVA results indicate that the type of forest (natural or plantation) does not significantly impact litter mass loss, as evidenced by a P-value of 0.879, suggesting that litter decompositions are similar between the two forest types. However, the season has a highly significant effect on litter mass loss ($P < 0.0001$), highlighting that seasonal variations are the primary drivers of litter decomposition **(Fig. 8).** Seasonal litter mass loss significantly differed ($p<0.001$) in both sites during the initial and final years, by an order of magnitude: monsoon > pre-monsoon > post monsoon. Siebenhart et al.,

(2025) predicted higher decomposition rates in warm, monsoonal ecosystems, aligning with Dutta and Agrawal, (2001) and Sarkar et al., (2016) who observed maximum litter mass loss during the rainy season, emphasizing the influence of seasonal precipitation on nutrient dynamics. Sohng et al., (2014) found similar results where leaf litter decomposition in temperate forests of NE Asia showed strong seasonal variation, with most decomposition occurring during summer.

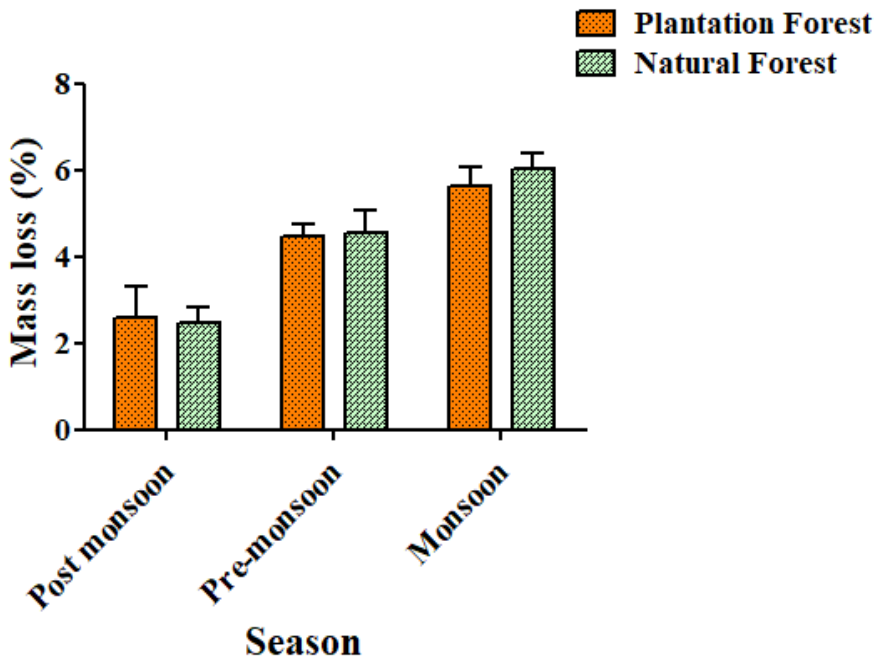


Fig. 8: Two-way ANOVA results display the effects of forest type and season on mass loss over two years (Mean ± SEM) at the study sites. While forest type shows no significant impact, season exhibits a highly significant effect (P < 0.0001), accounting for the majority of the variation.

Perez-Suarez et al., (2012) also observed that higher decomposition rates during the monsoon season are due to increased rainfall, air temperature and relative humidity. With the progression of time, the rate of leaf litter decomposition was increasing in the mixed forest than in the pure plantation environment suggesting that litter decomposition rates are primarily controlled by substrate quality (Pandey et al., 2007). Huang et al., (2020) and Farroq et al., (2022) reported similar observations with diverse litter mixtures. For instance, the coexistence of camphor trees with Masson pine in a mixed stand led to increased production of nutrient-rich litter and subsequently contributed to enhanced

nutrient cycling, thereby aiding in the restoration of soil fertility. The short-term experiment of 2 years not only demonstrates the early decomposition pattern in sequential order but also controls beginning litter substrate quality and environmental factors. Although temperature is the main element affecting the decomposition process in forest ecosystems, microbial diversity, the quality of the litter, and the physicochemical environment all have a significant impact on the breakdown of litter (Ahirwal et al., 2021). Weider et al., (2009) also demonstrated that litter decomposition rates in tropical forest ecosystems are strongly regulated by high temperature and rainfall.

It was also observed that the overall decomposition showed minimal variation across both sites, likely because they share similar environmental conditions, such as temperature, rainfall, and humidity **(Fig. 9).** Seasonal variation, especially shifts in precipitation regimes, significantly influences forest litter decomposition. A precipitation manipulation experiment in a subtropical evergreen forest demonstrated that extreme increases in wet season precipitation markedly enhanced litter decomposition rates, primarily due to alterations in moisture availability, elemental composition, and microbial activity (Ma et al., 2023). The observed seasonal variation in decomposition rates, with faster decomposition during the rainy season and slower rates in winter across much of Indian region can be largely attributed to the warm and moist conditions that favor microbial activity and organic matter breakdown (Pant and Tiwari, 1992; Devi and Yadav, 2007; Tripathi et al., 2009). Contrarily, the reduced decomposition rate during winter is linked to lower soil moisture and colder temperatures (Tripathi and Singh, 1992; Rawat et al., 2010).

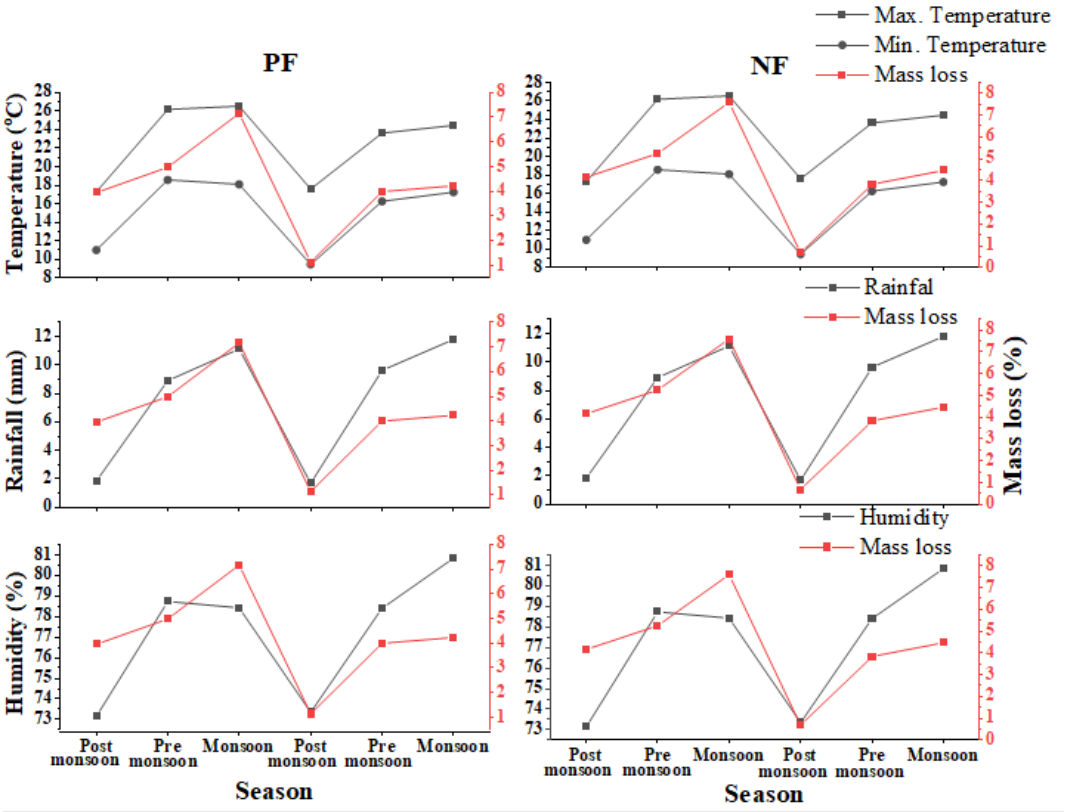


Fig. 9: Seasonal variation between litter mass loss with temperature, rainfall, and humidity in PF and NF over a two year period.

During the duration of the study, we quantified the decay rate constant (*k* expressed as unit of time day^{-1}) reflecting the fraction of litter mass lost per day due to decomposition for PF and NF, to assess the decomposition dynamics of litter in these distinct ecosystems. This unit facilitates direct comparisons of decomposition rates across different ecosystems; higher *k* values indicate quicker decomposition rates, resulting in shorter timeframes for litter breakdown, while lower *k* values point to slower processes. The *k* values for PF and NF enabled us to assess the differing decomposition dynamics between the two sites**.** The decay rate constant for PF was measured at 0.005 day^{-1}, translating to an annual decay rate of 1.83 year^{-1}. This decay rate indicates a relatively slow decomposition process in the PF. The half-life (t_{50}) - the time required for 50% of the litter mass to decompose was found to be 132 days. The time taken to reach 95% decomposition (t_{95}) and 99% decomposition (t_{99}) were 573 days and 956 days, respectively, reflecting a gradual and extended decomposition phase in this environment. In comparison, the decay

rate constant for NF was calculated to be 0.007 day^{-1}, which equates to a more rapid annual decay rate of 2.56 $year^{-1}$. This suggests that litter decomposition in the NF occurs at a faster pace than in the PF. The corresponding t_{50}, t_{95}, and t_{99} values for NF were recorded at 99 days, 428 days, and 714 days, respectively. These results indicate that the litter in the NF decomposes more quickly, allowing for a shorter duration for substantial mass loss compared to the PF. However, this model assumes a constant rate of decomposition, which may not fully capture the complexities of the actual decomposition process in a natural forest. In reality, litter decomposition in the field is influenced by various environmental factors, such as temperature, moisture, microbial activity and litter quality, which can lead to deviations from the model's predictions. In our study, the decay constant was found to be 1.83 $year^{-1}$ in the PF and 2.56 $year^{-1}$ in the NF. These findings align with those of Keerthika et al., (2024), who reported decay constants of 2.85 $year^{-1}$ for *Tectona grandis* and 1.1 $year^{-1}$ for *Melia dubia* twigs. Similarly, Ge et al. (2013) noted that k-values ranging from 0.35 to 0.36 a^{-1} accounted for 30% of the decomposition process in temperate and Mediterranean regions, while k-values of 2.33 a^{-1} represented 90% of the decomposition process in tropical regions. Throughout the study period, there aren't many notable variations in PF and NF, indicating that all ecosystem processes have high productivity under favourable conditions. Even so, it is argued that additional research on the long-term decomposition process is necessary in order to fully comprehend the actual process of decomposition.

Litter nutrient dynamics

The chemical composition of initial litter component was analysed in the beginning of the experiment *i.e.* prior to its placement in the litter bags (during the month of March, 2019) to assess the seasonal changes of each composition over two years of study. Accordingly, initial composition of litter in the PF was recorded for Carbon (44.50%), Lignin (22.75%), N (1.65%), P (1.01%), K (0.32%), C/N (27.04%), L/N (13.83%). However, in NF, the constituents are comparatively higher as estimated for Carbon (49.00%), Lignin (24.00%), N (2.00%), P (1.16%), K (0.38%), C/N (24.55%), L/N (12.01%). During the initial phase, the decomposition of leaf litter is predominantly affected by the content of lignin, which constitutes 22.75 and 24 percent in PF and NF as well as the nitrogen content, accounting for 1.65 and 2 percent in PF and NF respectively.

Higher levels of concentration for carbon, lignin, nitrogen, and potassium were observed during the monsoon and pre-monsoon seasons at both study sites **(Table 2).** Phosphorus similarly exhibited increased concentrations during the pre-monsoon and monsoon seasons, but in the second year, it demonstrated higher levels during the post monsoon season at both sites. The C:N ratio showed a distinctive concentration peak in the post monsoon season at both study sites. Furthermore, the L:N ratio showed higher concentrations in both PF and NF throughout the post monsoon season.

Table 2: Chemical composition of leaf litter under different study sites (Mean±SD, n=3). Different lower-case letters indicate significant differences according to one-way ANOVA.

Site	Year	Season	Carbon (%)	Lignin (%)	N (%)	P (%)	K (%)	C/N (%)	L/N (%)
PF	I year	Post monsoon	43.12±1.69^{b}	22.19±2.32^{b}	1.39±0.22^{b}	0.39±0.25^{b}	0.30±0.02^{a}	31.73±5.11^{a}	16.12±0.96^{a}
		Pre-monsoon	44.95±1.20^{ab}	23.35±0.79^{b}	1.72±0.07^{a}	0.97±0.07^{a}	0.34±0.01^{a}	25.67±0.18^{b}	13.34±0.56^{b}
		Monsoon	46.51±1.00^{a}	26.35±0.90^{a}	1.78±0.10^{a}	0.83±0.09^{a}	0.34±0.01^{a}	25.95±1.95^{bc}	14.71±0.97^{bc}
	II year	Post monsoon	39.69±0.89^{a}	11.64±1.08^{c}	0.55±0.07^{b}	0.30±0.08^{a}	0.23±0.02^{a}	73.26±9.11^{a}	21.62±4.45^{a}
		Pre-monsoon	40.75±1.78^{a}	19.60±2.04^{a}	1.00±0.21^{a}	0.28±0.06^{a}	0.29±0.00^{a}	41.60±7.28^{b}	20.35±6.25^{a}
		Monsoon	39.86±1.59^{a}	15.24±1.80^{b}	0.79±0.09^{c}	0.22±0.03^{a}	0.25±0.01^{a}	50.95±4.53^{c}	19.46±2.48^{a}
NF	I year	Post monsoon	49.36±0.78^{b}	27.17±2.08^{c}	1.47±0.22^{b}	0.48±0.35^{b}	0.34±0.01^{a}	34.08±4.51^{a}	18.78±3.20^{a}
		Pre-monsoon	52.50±2.15^{a}	25.97±2.78^{b}	2.01±0.14^{a}	1.21±0.03^{a}	0.37±0.02^{a}	26.23±2.22^{b}	12.93±0.96^{b}
		Monsoon	52.66±1.45^{a}	29.14±1.62^{a}	2.13±0.49^{a}	1.23±0.21^{a}	0.42±0.03^{a}	25.71±5.60^{bc}	14.20±3.05^{bc}
	II year	Post monsoon	41.71±2.33^{b}	10.28±1.20^{b}	0.55±0.08^{bc}	0.27±0.02^{a}	0.23±0.03^{a}	77.82±14.68^{a}	19.00±2.89^{bc}
		Pre-Monsoon	45.87±1.81^{a}	19.63±1.51^{a}	0.97±0.16^{a}	0.24±0.02^{a}	0.31±0.02^{a}	48.17±8.10^{b}	20.47±2.02^{b}
		Monsoon	43.73±1.71^{c}	16.91±1.54^{c}	0.64±0.07^{b}	0.22±0.05^{a}	0.27±0.01^{a}	69.20±9.71^{c}	26.59±2.47^{a}

The two-way ANOVA results indicate that effect of forest type and season significantly influence the levels of carbon, lignin, N, P, and K across two different study sites **(Fig. 10).** However, the results also show that season plays a more prominent role in determining nutrient levels ($p < 0.001$).

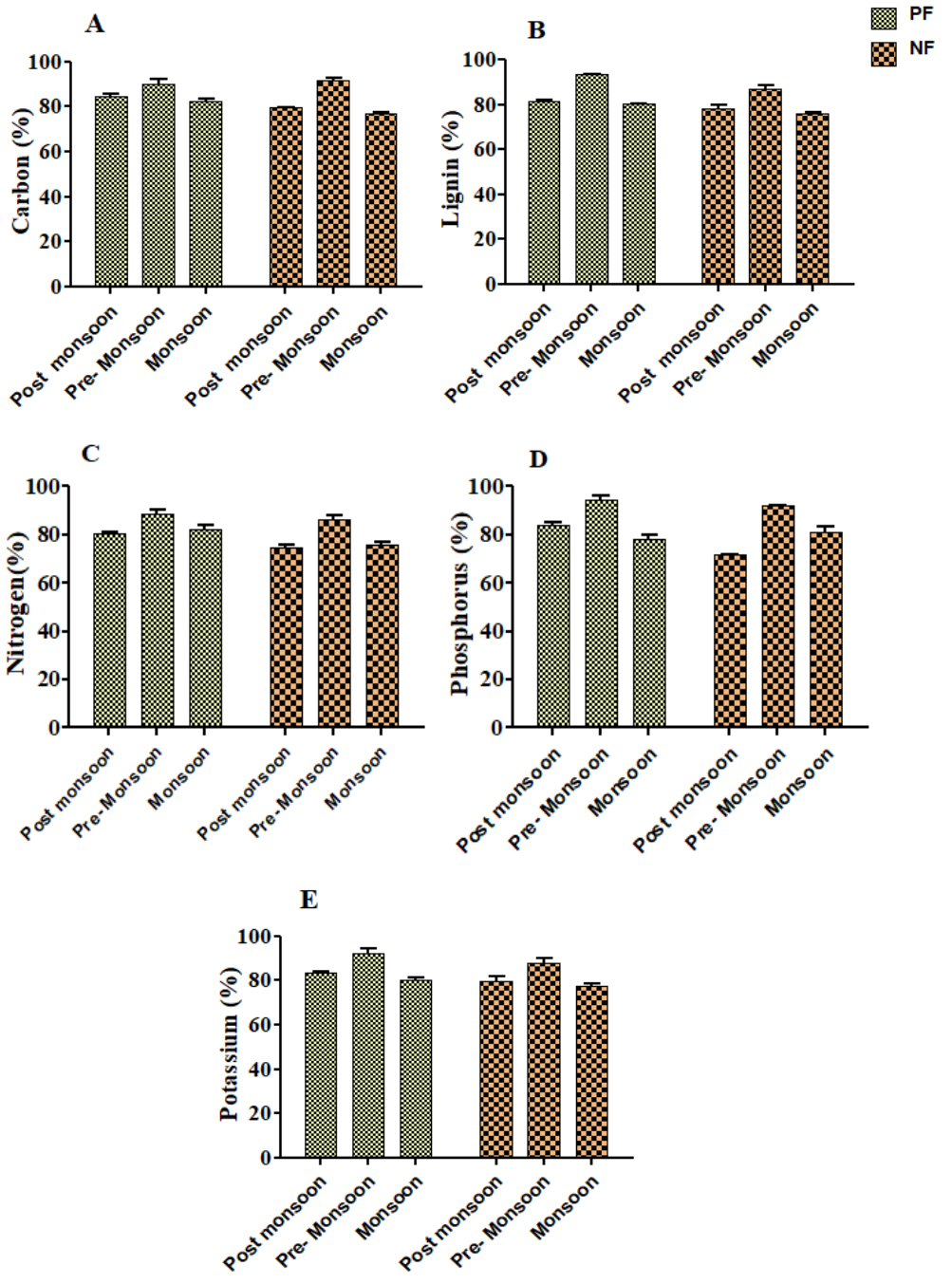


Fig. 10. Two-way ANOVA showing seasonal variation over two years in the remaining nutrient levels (Mean ± SEM) for (A) Carbon (%), (B) Lignin (%), (C) Nitrogen (%), (D) Phosphorus (%), and (E) Potassium (%) at both study sites.

The concentration of C, lignin, N, P, and K in both study areas was higher in the initial year and experienced a decline in the following year. Organic carbon, constituting approximately 50 percent of the post monsoon weight of organic litter, consistently constituted the maximum proportion. In PF, a persistent increase in N concentration was observed up to 213 days, i.e., the first 7 months (April to October). However, in NF, it exhibited fluctuating pattern, characterized by alternating periods of decrease and increase in concentration till 182 days i.e., first 6 months (April-September), and thereafter a gradual decline in N concentration was observed till the end of the decomposition period in both the study areas. Similar trends were also observed in the concentrations of C and lignin across both study regions (Fig. 10). Sarker et al., (2018) also find the similar trend wherein nitrogen and potassium concentrations decreased during decomposition of *Terminalia arjuna* and *Toona ciliate.*

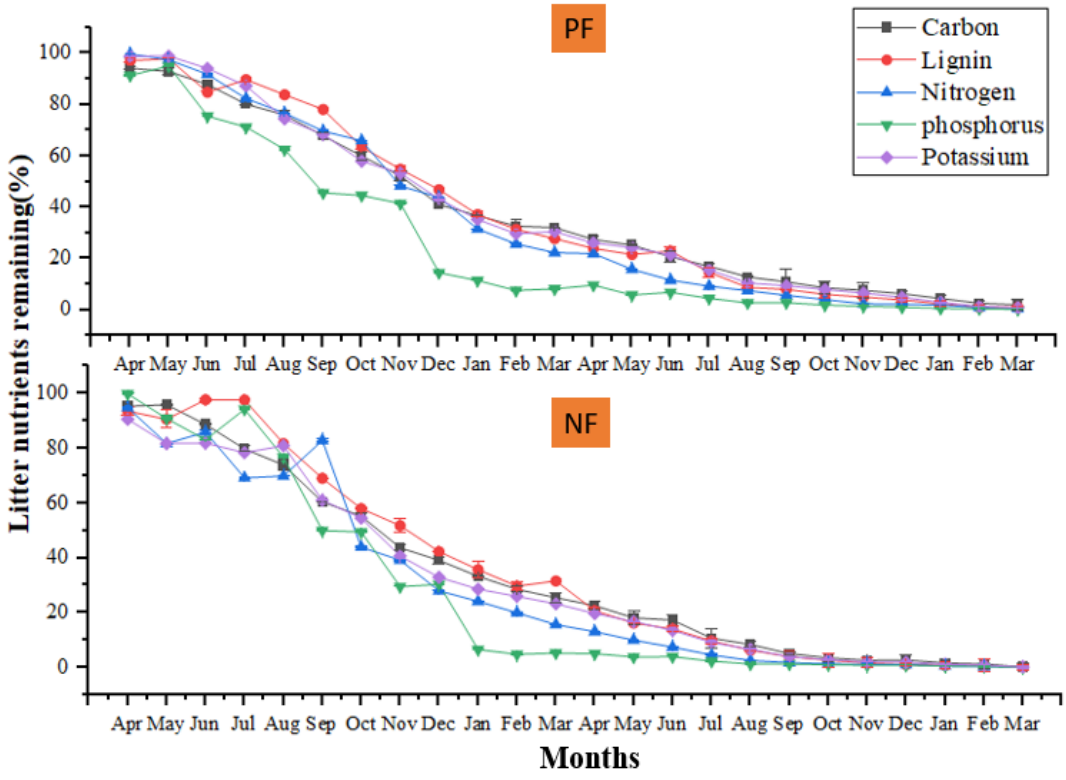


Fig. 11: Temporal variations in litter parameters throughout the two-year decomposition process

Mass loss with soil and litter parameters

The correlation between litter mass loss (%) and various soil parameters in PF and NF, highlights the key factors influencing litter decomposition **(Fig.12).** In both forest types, ST shows a moderate positive correlation with mass loss (PF: $p = 0.002$; NF: $p = 0.004$). MC also positively correlates with mass loss in both forests, with a higher effect in NF ($p < 0.0001$). These findings are consistent with previous studies (Onwuka and Mang, 2018; Liu et al., 2022), which emphasize that soil temperature and moisture are critical in altering the rates of organic matter decomposition and the mineralization of various organic matter. Soil pH is more strongly correlated with decomposition in PF ($p < 0.0001$) than in NF ($p = 0.008$). This aligns with findings by Tao et al., (2019), who reported that soil pH, along with its associated base cations and organic acids, may directly affect decomposition by controlling decomposer composition and activity and indirectly by influencing plant traits. OC is significantly related to mass loss in both forests, but especially in NF ($p < 0.0001$). Among nutrients, N and K show stronger correlations with mass loss in NF (N: $p=0.001$; K: $p = 0.000$) than in PF. P is not significantly correlated with mass loss in PF ($p = 0.121$) but is moderately significant in NF ($p = 0.002$). Hu et al., (2023) demonstrated that the addition of N, P, and combined N+P treatments significantly enhanced the decomposition of litter, lignin, and cellulose. Similarly, Cleveland et al., (2011) found significant correlations between soil and foliar phosphorus concentrations and litter decomposition rates. Overall, the results demonstrate that soil nutrient availability and quality are critical drivers of litter mass loss and nutrient cycling.

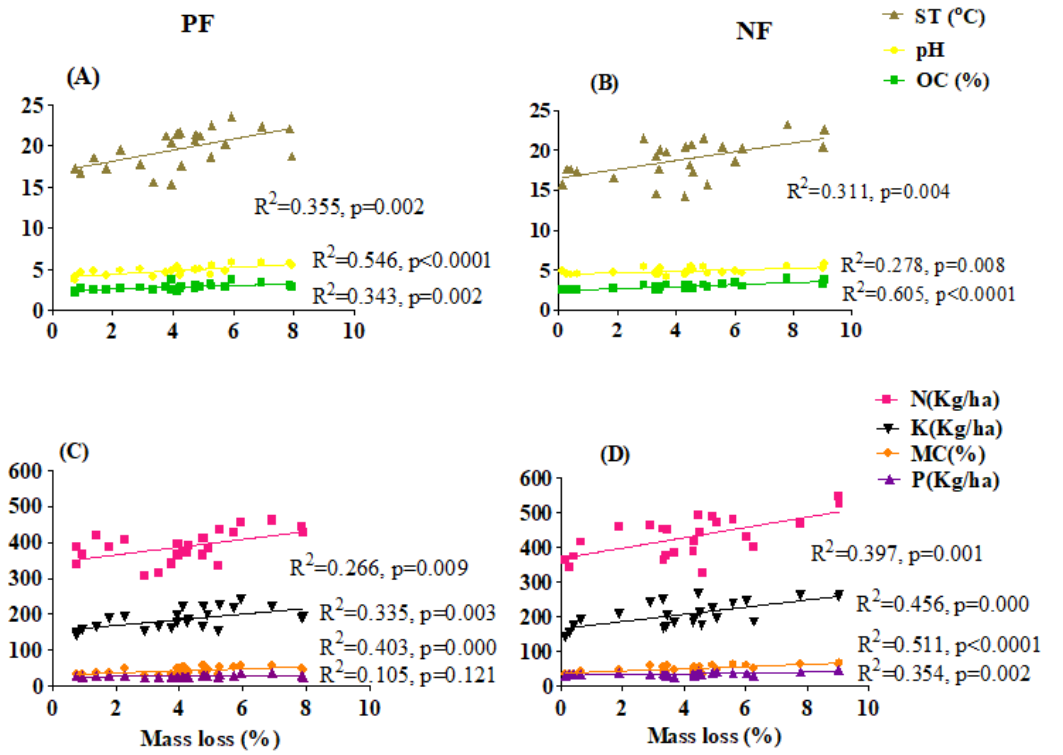


Fig. 12: Pearson correlation coefficients (R) and p-values (P) demonstrate the relationships between soil parameters and litter mass loss at two distinct study sites. Panels A and C display soil parameters for PF, while Panels B and D represent NF. Except P in the PF, all soil parameters exhibit statistically significant correlations with litter mass loss ($p < 0.05$).

Regression analyses between litter mass loss and various litter quality parameters shows that both C and lignin are positively correlated with mass loss in PF and NF **(Fig. 13).** lignin shows a stronger correlation with mass loss in both PF and NF ($p < 0.0001$). Nutrients N, P, and K all exhibit positive correlations with litter mass loss. In PF, N ($p = 0.001$) and K ($p < 0.0001$) show strong correlations, while P is moderately correlated ($p = 0.004$). In NF, N ($p < 0.0001$), P ($p = 0.007$), and K ($p < 0.0001$) also show positive relationships. Contrary to the commonly observed inhibitory role of lignin in litter decomposition, our results showed a significant positive correlation between lignin content and litter mass loss. This unexpected trend may be attributed to favorable environmental conditions such as high soil moisture and temperature during the monsoon season, which can enhance microbial activity and promote lignin breakdown. Similar findings have been reported where rapid decomposition can occur despite high lignin content (Prescott, 2010; Klotzbucher et al., 2011). Moreover, in mixed-litter systems, nutrient transfer and microbial priming may facilitate the co-

decomposition of lignin-rich materials (Gartner and Cardon, 2004). Litter mixtures effect sizes indicated that at times litter mixtures decompose slower or faster than the expected mass loss based on single-species litter (Njoroge et al., 2021).

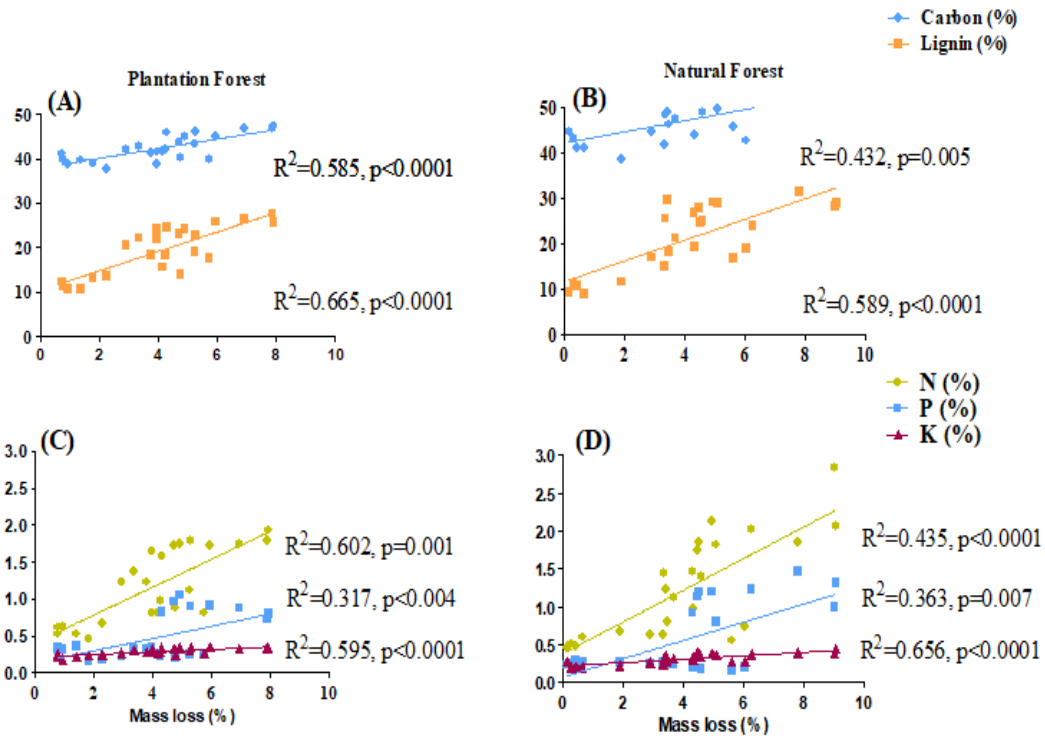


Fig. 13: Multiple regression analysis of litter parameters and mass loss, with panels (A) and (C) representing the PF, while (B) and (D) representing the NF. All litter parameters exhibit significant positive correlations with mass loss ($p<0.005$).

Soil microarthropods, mainly Acari and Collembola, are key drivers of soil ecological processes such as litter decomposition, nutrient cycling, and microbial regulation, and their population dynamics changes in abundance, diversity, and community structure are shaped by both abiotic and biotic factors (Fujii and Takeda, 2017; Menta and Remelli, 2021). Temperature, moisture, pH, and soil organic matter strongly influence their seasonal fluctuations, with higher abundance often recorded during warm and moist periods (Guo et al., 2022; Junggebauer et al., 2024). Microarthropods enhance microbial communities during litter decomposition by redistributing organic matter, disrupting aggregates, and increasing surface area for leaching, thereby promoting microbial activity and turnover (Soong and Nielsen 2016). Importantly, soil microarthropods act as bioindicators of soil health (Remelli et al., 2024; Gallese et al., 2025; Rodriguez-Pajares et al., 2025)**,** reflecting environmental disturbances, land management practices, and climate change impacts. Understanding the population dynamics of soil microarthropods is essential, as it highlights patterns of soil biodiversity and ecosystem resilience while also offering critical insights for sustainable soil management, conservation of ecosystem services, and predicting ecological responses under changing environmental conditions. In the present study, the microarthropods recorded from the two forest ecosystems (natural and plantation) were classified into two major components: (A) soil microarthropods and **(**B) litter microarthropods. Based on their density, abundance, and overall contribution to the total community, two dominant groups were identified viz. Acarina and Collembola which accounted for the majority of individuals. Alongside these, other taxa such as Myriapoda, Diplopoda, Araneae, Symphyla, Isopoda, Diplura, Coleoptera, Pseudoscorpiones, Chilopoda, and Hymenoptera were also recorded, though their population densities remained consistently low throughout the study period. These less abundant groups were therefore collectively categorized as **"**other microarthropods**."**

i. Collembola
ii. Other microarthropods

Taking into consideration of litter and soil microarthropods from both study sites a total of 34 species of Acarina, viz. Trombidiidae (a), Trombidiidae (b), Bdellidae *Trichotocepheus erabuensis*, *Pergalumna (P.) brasiliensis*,, Laelapidae (a), Laelapidae (b), Dinychidae, *Lepidacarus ornatissimus*, *Jacotella ornate*, *Leptus* sp.,

Tydeus sp., Trombidiformes (a), Trombidiformes (b), Trombidiformes (c), Trombidiformes (d), *Urodiaspi*s sp., Rhagidiidae (a), Rhagidiidae (b), *Microtrombidium* sp. *Galumna (G.) flabellifera, Trombicula sp., Scheloribatidae, Erythracaridae, Macrocheles sp., Tetranychus sp.,* Phthiracaridae, *Gamasellus* sp., *Urobovella* sp, *Gamasodes* sp., *Carinogalumna clericata*, Galumnidae, *Dendropectinat*a, *Rimachensis*, *Allothrombium* sp. Wheras, a total of 14 species Collembola were identified such as *Callyntrura vestita Uchida, Callyntrura semiviolacea, Dicranocentrus sp, Acanthurella satkosiaensis, Lepidocyrtus sp.* (a), *Seira sp, Lepidocyrtus heterolepis, Lepidocyrtus sp* (b), *Lepidocyrtus himalayanus, Alloscopus* sp, *Neanuridae***,** *Onychiuridae, Hypogastruridae*, *Bourletiellidae* and 14 belonging to other groups have been recorded from both the study sites **(Table 3**).

Studies on soil microarthropods have documented considerable variation in their diversity and abundance across habitats and regions. Gwiazdowicz et al., (2023) identified 17 species of microarthropods and demonstrated that community composition varied not only among localities but also across different microhabitats. In India, Acharya and Basu, (2014) recorded 17 species under 9 genera and 14 families of oribatid mites, while in a subsequent study, Acharya and Basu, (2016) reported a much richer assemblage, with 44 species belonging to 37 genera, highlighting the heterogeneity of oribatid communities. Similarly, Acharya and Datta, (2019) reported 23 species of oribatid mites from Himachal Pradesh, contributing to a total of 43 species known from the state. Habitat-specific studies also reveal strong differences: Das, (2021) observed that microarthropods were most abundant in forest soils and least abundant in rubber plantations, with oribatid mites (32%) as the dominant group followed by Collembola (24%). This pattern is consistent with the findings of Sarkar et al., (2016a) and Syed et al., (2023), both of whom noted Oribatida as the most abundant order, again followed by collembolans. Similarly, Rakshit and Chanda, (2017) reported habitat-linked diversity, with 24 species of oribatid mites in wastelands, 20 species in fodder fields, and 16 species in sugarcane fields. On a broader taxonomic scale, Todria et al., (2021) identified 82 species of Acari, with both species richness and individual density being highest in natural grasslands and lowest in managed grasslands, whereas Gonzalez-Mace and Scheu, (2018) recorded 27 species of Collembola, and Gwiazdowicz et al., (2023) recorded 17 species of microarthropods (1 Mesostigmata, 9 Oribatida, 7 Collembola species) identified

highlighting the ecological variability and habitat dependence of soil microarthropod diversity. The higher diversity of microarthropods in natural forests may be attributed to the closed canopy with diverse vegetation cover, greater availability of food resources, accumulation of litter, and favorable physico-chemical conditions that promote their population growth, and the composition of soil fauna is further shaped by forest type and litter depth, as studies have shown that oribatid mites attain higher abundance and species richness in recalcitrant, slowly decomposing litter than in nutrient-rich substrates that decompose rapidly, emphasizing the critical role of litter thickness and microhabitat heterogeneity in structuring soil faunal communities (Eissfeller et al., 2013).

Table 3: Number of species recorded in Litter and Soil habitats at both the study sites.

Microarthropods	Litter (NF)	Litter (PF)	Soil (NF)	Soil (PF)
Acari	34	13	12	10
Collembola	14	7	8	5
Others	14	10	12	9

Acari

Monthly population density of Acarina in NF and PF

Litter Acarina abundance in a natural forest over two years show clear seasonal variation with generally high values in first year from April through October, peaking between July and September **(Fig. 14)**. For instance, population density rises from 6.81×10^2 m^{-2} in April to 12.44×10^2 m^{-2} in July and remains high at 13.63×10^2 m^{-2} in both August and September 11.25×10^2 m^{-2}. After November 10.37×10^2 m^{-2} , the abundance declines, dropping to 4.74×10^2 m^{-2} in December. In the second year, a similar pattern is observed with high values such as 13.63×10^2 m^{-2} in both June and August, followed by a decrease to 2.07×10^2 m^{-2} in January. However, in case of litter Acarina in PF indicate relatively low and stable population levels, generally ranging between 0.88×10^2 m^{-2} and 4.59×10^2 m^{-2} across months. Peak abundances were recorded in July (4.59×10^2 m^{-2}) and May (4.44×10^2 m^{-2}) of the first year, with slightly elevated values also occurring in April and August. In contrast, the lowest abundances were observed in January and February, when values fell below 1.0×10^2 m^{-2}.

The two-year data on Soil Acarina population density in NF reveal a distinct seasonal pattern. Abundance remains relatively high from April–October, with peaks such as 26.51×10^2 m^{-2} in October and values exceeding 18×10^2 m^{-2} in June and September. This is followed by a sharp decline during the month of November–February, when the lowest levels are observed, particularly in December (3.78×10^2 m^{-2}) in first year and January (5.3×10^2 m^{-2}) in second year. Whereas, in PF pattern shows distinct seasonal fluctuations, with prominent peaks during August–October in first year and again in May–June in second year. The highest values were observed in June of the second year (20.07×10^2 m^{-2}) and in August of the first year (15.9×10^2 m^{-2}). In contrast, the lowest abundance occurred in January–February, reaching as low as 2.27×10^2 m^{-2} and 3.03×10^2 m^{-2}.

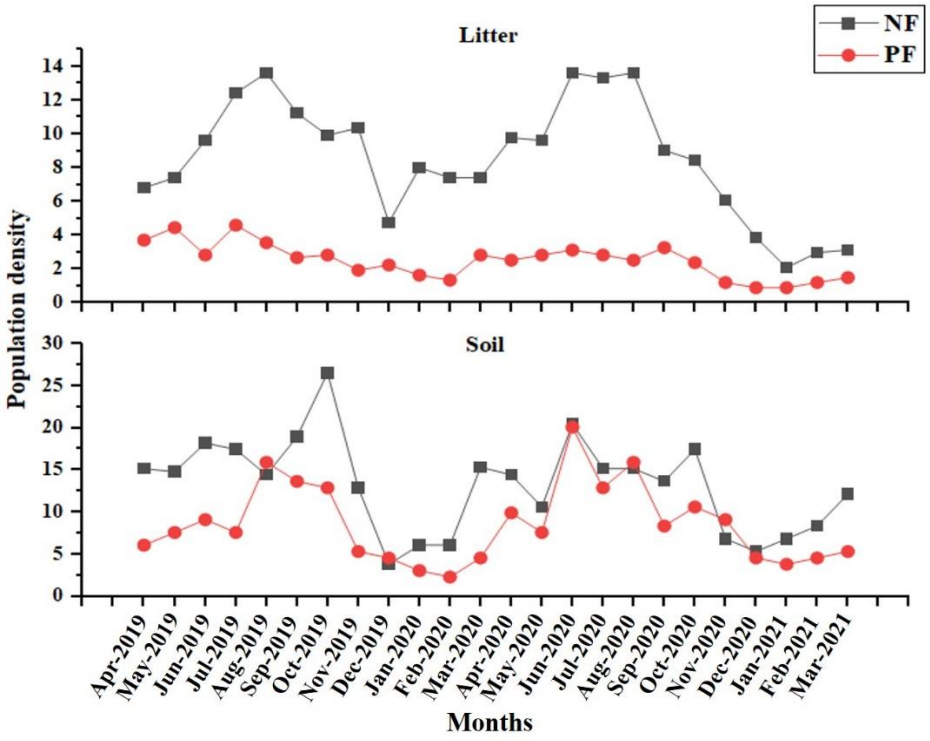


Fig. 14: Monthly fluctuation of litter and soil Acarina population density (Number × 10^2m^{-2}) in NF and PF ecosystems.

ANOVA results for the seasonal population density of Acari in both litter and soil across NF and PF shows that Acari densities are lowest in the post-monsoon season, rise significantly in the pre-monsoon, and reach their highest values during the monsoon season **(Fig. 15).** Panels A and B represent litter habitats, while Panels C and D represent soil habitats, showing clear seasonal differences in population

density. Panel A depicts litter Acarina in NF ($p = 0.002$, $R = 0.56$), while Panel B shows litter Acarina in PF with a stronger significance ($p < 0.0001$, $R = 0.60$). Panel C represents soil Acarina in NF ($p = 0.0001$, $R = 0.57$), and Panel D illustrates soil Acarina in PF ($p = 0.0003$, $R = 0.54$). The statistical analysis of our study indicates that Acari densities increase significantly from post-monsoon to pre-monsoon and monsoon seasons ($p < 0.05$), whereas no significant difference is observed between pre-monsoon and monsoon periods. Overall, Acari populations are consistently higher than those of Collembola in natural forests compared to plantation forests, and both habitats exhibit marked seasonal fluctuations. This pattern aligns with findings by Tsurho and Ao, (2014a), who reported that soil Acarina densities were greater in natural forests, reaching 231.37×10^2 m^{-2} during the rainy season, 116.20×10^2 m^{-2} in summer, and 77.25×10^2 m^{-2} in winter. Similarly, Junggebauer et al., (2024) observed that drought-prone soils during dry winters led to a significant decline in oribatid mite populations. Seasonal variation in Acari community structure was also reported by Tiwari and Monika, (2024), who noted that although overall abundance patterns were similar across habitats, summer populations fluctuated more in reclaimed forests than in natural forests. Supporting this, Malica et al., (2024) found higher mesostigmatid mite abundance in October than in July, reflecting the influence of soil moisture, while emphasizing that wet seasons provide the most favorable conditions for mesostigmatid mites. Vaisanen and Markkula, (2024) also reported that oribatid mite densities were highest in winter (2,000 individuals/m^2) and lowest in summer (500 individuals/m^2), highlighting species-specific responses to seasonal changes. Borah and Kakati, (2014) similarly revealed that vertical and seasonal distribution of soil Acari was more pronounced in natural forests than in degraded sites, with Acarina dominating the community, constituting 39.26% in natural forests and 37.51% in degraded forests. Additionally, Chen et al., (2024) demonstrated that seasonal effects on soil oribatid mite communities were stronger than the influence of tree diversity, indicating that abiotic factors and resource availability are the primary drivers of oribatid community structure.

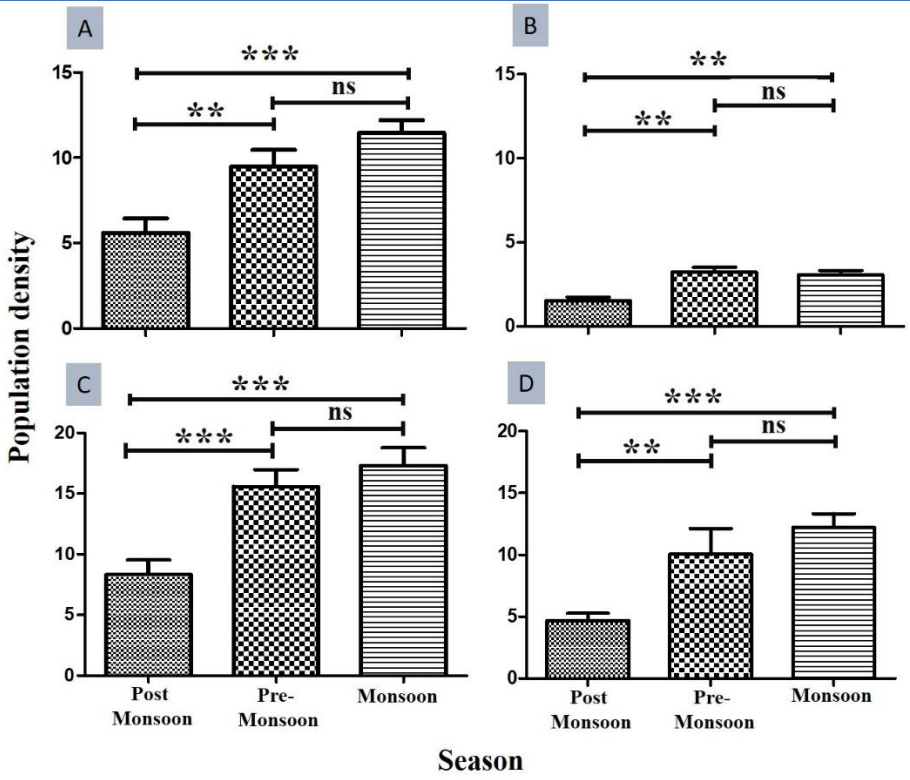


Fig. 15: Analysis of variance showing seasonal variation of Acari in litter and soil. Panels (A) and (B) represent litter acarina in NF and PF, respectively, while panels (C) and (D) represent soil acarina in NF and PF, respectively.

Collembola

Monthly population density of Litter and Soil Collembola in NF and PF.

The data for monthly litter Collembola population in a NF over two years show a clear seasonal pattern. Abundance generally increases from April, rising to peak values in June- September in the first year **(Fig. 16)**. After October, there is a steady decline in population density, reaching the lowest values during the winter months of December to February, with values as low as 1.92×10^2 m^{-2} and 2.07×10^2 m^{-2}. The population begins to rise again in the following year i.e March and April, indicating a recurring annual cycle where litter Collembola population is higher in warmer and wetter months and lower during colder, drier periods. In PF, the highest values occur in the warmer months, with peaks of 3.85×10^2 m^{-2} in July (first year) and 4.51×10^2 m^{-2} in May and 4.07×10^2 m^{-2} in September during the second year. Overall, litter Collembola in PF reached as low as 0.8×10^2 m^{-2} in January. Soil Collembola abundance in a NF over two years show abundance increase from April 2019, peaking

in the summer months of May, June, July 13.57×10^2 m^{-2}, and August 17.34×10^2 m^{-2} with the lowest value recorded as 2.26×10^2 m^{-2} in January. In PF Abundance peaks in June (9.04×10^2 m^{-2}), with moderately high in the month of June -September. There is a sharp decline in the months from November to February, with values dropping to zero in December and January during first year and January in second year.

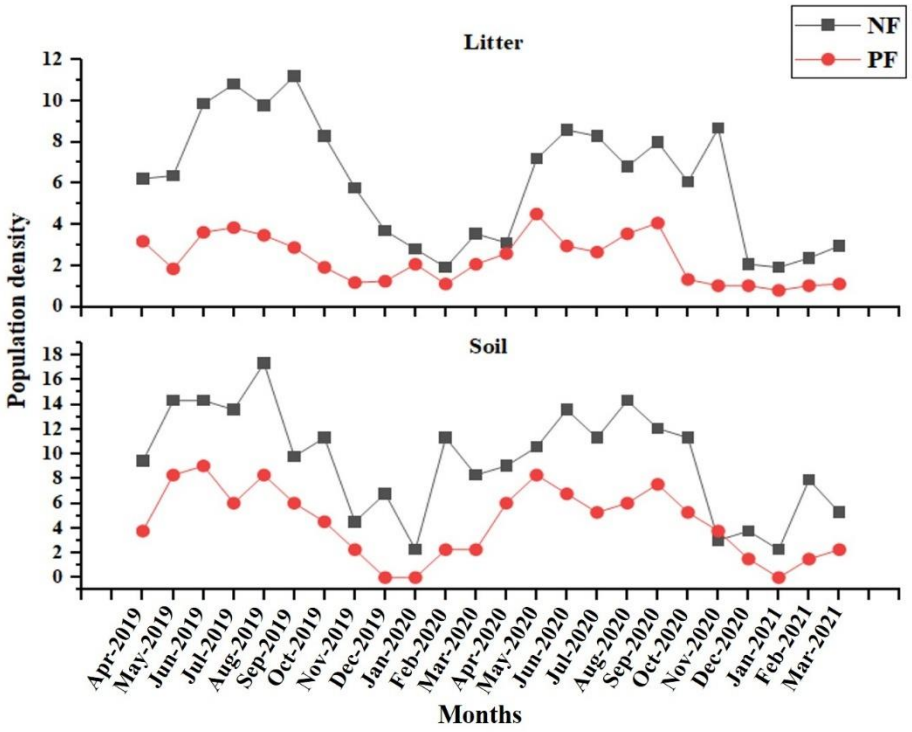


Fig. 16: Monthly fluctuation of litter and soil Collembola population density (Number × 10^2m^{-2} in NF and PF ecosystems.

Seasonal variation of Collembola in NF and PF.

ANOVA results shows that across all panels, Collembola population density is lowest in the post-monsoon season, rises significantly in the pre-monsoon, and generally peaks in the monsoon **(Fig. 17).** Panels A and B represent litter habitats, while Panels C and D represent soil habitats, showing clear seasonal differences in population density. Panel A depicts litter Collembola in NF ($p = 0.001$, $R = 0.56$), while Panel B shows litter Collembola in PF with a stronger significance ($p < 0.0001$, $R = 0.59$). Panel C represents soil Collembola NF ($p < 0.0001$, $R = 0.64$), and Panel D illustrates soil Collembola in PF ($p<0.0001$, $R = 0.76$). Statistical markers indicate the significance of differences ($P<0.05$). The difference between pre-monsoon and monsoon is not significant, meaning densities stabilize at their highest between these

two seasons. Therefore, the ANOVA demonstrates Collembola populations are lowest after the monsoon, grow sharply before the monsoon, and remain high through the monsoon. Natural forests exhibit higher densities than plantation forests, evident in greater population values in panels A and C compared to B and D. Our results highlight that microarthropod population density is considerably higher in natural forests compared to plantation forests, as soil fauna diversity typically declines following forest conversion, largely due to changes in litter quality and moisture (Wen et al., 2025). Several studies corroborate this pattern. For instance, Bhagawati et al., (2021) reported that Collembola densities reached their peak in summer and steadily declined through autumn and spring, attaining the lowest values in winter across forest, vegetable, and tea ecosystems, with densities ranging from 340.91 to 20.00 ind./m². A similar seasonal pattern was documented by Bhagawati et al., (2018) in Majuli, Assam, where Collembola density peaked in summer (196.36 ind./m²) and dropped to its minimum in winter (39.09 ind./m²), with monthly variation showing the highest abundance in August (206.82 ind./m²) and the lowest in February (27.27 ind./m²). Lisa et al., (2022) further confirmed this seasonal trend, reporting maximum summer densities of 340.91, 172.73, and 86.36 ind./m² in forest, vegetable, and tea ecosystems, respectively, while minimum densities were recorded in winter (81.82, 34.55, and 20.00 ind./m²). The role of habitat type in regulating Collembola populations is also well established. Paul et al., (2011) found that forests supported consistently higher Collembola density and diversity than agroecosystems, with populations peaking from spring to autumn and declining in winter. On a broader scale, Mawan et al., (2022) showed that lowland rainforests harbored the highest Collembola abundance (53.4 ± 30.7 ind./m²), more than five times greater than in rubber plantations and over ten times greater than in oil palm plantations, while jungle rubber supported intermediate values. Similarly, Silva et al., (2016) demonstrated that Collembola community life-form traits varied significantly with land-use type, with forests favoring a greater proportion of eu-edaphic species compared to grasslands and arable lands. Recent findings further strengthen this evidence. Zheng et al., (2025) observed that primary forests harbored significantly higher Collembola abundance and diversity (Shannon–Wiener index) than secondary forests, with several rare groups found exclusively in primary forests. Susanti et al., (2021) also emphasized that widespread conversion of natural forests into intensively managed monoculture

plantations in the tropics alters ecological niches, simplifies trophic structures, and reduces soil biodiversity, thereby threatening ecosystem stability. Likewise, Kurniawan et al., (2025) reported that the replacement of tropical rainforests with oil palm and rubber plantations significantly reduced oribatid mite density and species richness in Sumatra, underscoring the broader impacts of land-use change on soil mesofauna. Seasonal dynamics further interact with land-use systems to regulate Collembola populations. Susanti et al., (2024) noted that Collembola density in litter peaked at the onset of the wet season, while soil populations showed comparatively little variation; both density and community composition were strongly influenced by seasonal changes in rainforest and plantation ecosystems. Together, these studies highlight the combined influence of seasonality, habitat type, and land-use intensity in shaping soil microarthropod communities.

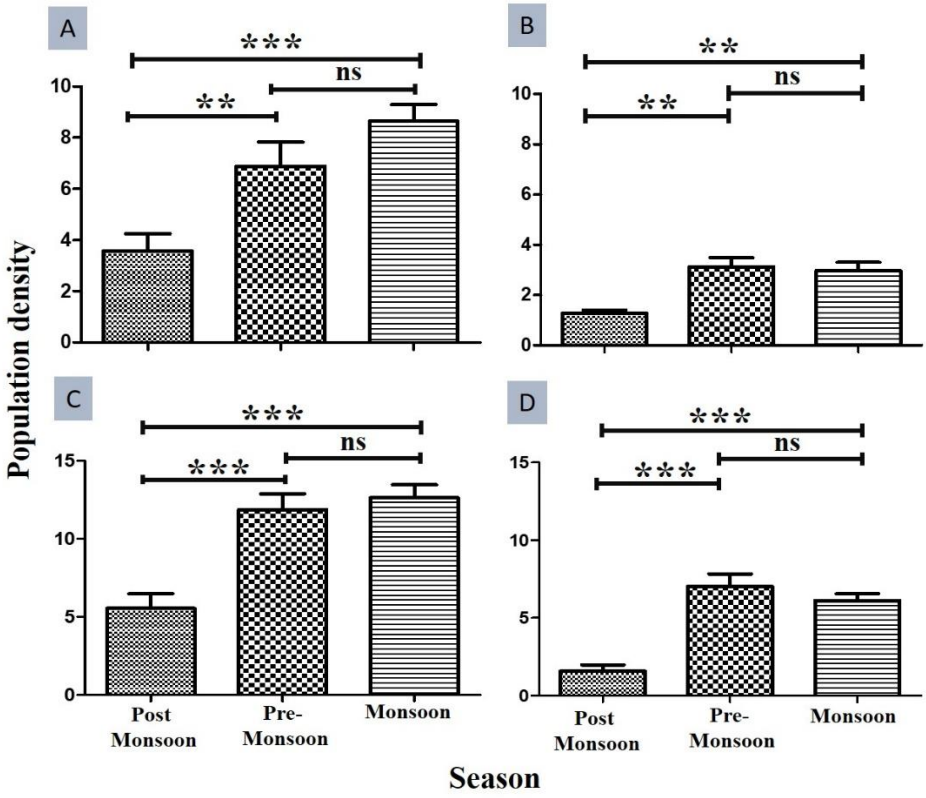


Fig. 17: Analysis of variance showing seasonal variation of Collembola in litter and soil. Panels (A) and (B) represent litter Collembola in NF and PF, respectively, while panels (C) and (D) represent soil Collembola in NF and PF, respectively.

Other microarthropods

Monthly population density of Other microarthropods in Litter and Soil for NF and PF.

In litter of NF, the population density of other microarthropods reached its maximum in August (8.74×10^2 m^{-2}) and declined to the lowest level in December (1.33×10^2 m^{-2}). In PF, a similar seasonal trend was observed, with a peak in August (4.74×10^2 m^{-2}) and the lowest abundance in December (1.03×10^2 m^{-2}) (**Fig. 18)**. The abundance of other soil microarthropods in the NF reaches highest densities during the months (June–October), particularly in June ($23.38 \times 10^2 m^{-2}$) and July ($22.62 \times 10^2 m^{-2}$). the lowest values occurred in May ($6.03 \times 10^2 m^{-2}$) . In PF, populations increased steadily from April ($7.54 \times 10^2 m^{-2}$) through the monsoon, peaking sharply in September ($21.87 \times 10^2 m^{-2}$), after which numbers declined reaching the lowest in January ($4.52 \times 10^2 m^{-2}$) and December ($5.27 \times 10^2 m^{-2}$). Overall, microarthropod population density in PF was lower compared to NF

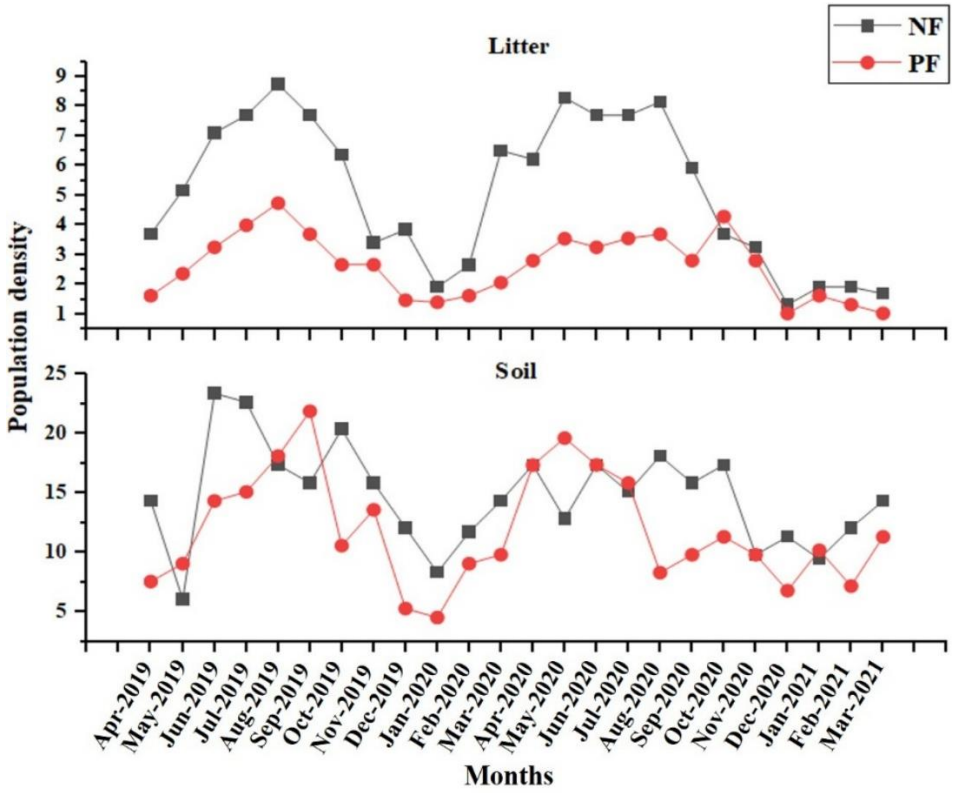


Fig. 18: Monthly fluctuation of Other microarthropods population density (Number × $10^2 m^{-2}$) in NF and PF ecosystem.

Seasonal variation of Other microarthropods in Litter and Soil for NF and PF.

In the ANOVA results for other microarthropods, Panels A and B represent litter habitats, while Panels C and D represent soil habitats, showing clear seasonal differences in population density. Panel A depicts other litter microarthropods in NF ($p < 0.0001$, $R = 0.62$), while Panel B shows other litter microarthropods in PF with significance ($p < 0.0001$, $R = 0.65$). Panel C represents other soil microarthropods NF ($p = 0.007$, $R = 0.37$), and Panel D illustrates other soil microarthropods in PF ($p = 0.01$, $R = 0.32$) **(Fig.19)**. Overall, these results demonstrate a strong seasonal effect, where microarthropod populations in both litter and soil are depressed in Post-Monsoon but thrive under the more favourable conditions of Pre-Monsoon and Monsoon, with similar trends observed across both habitats.

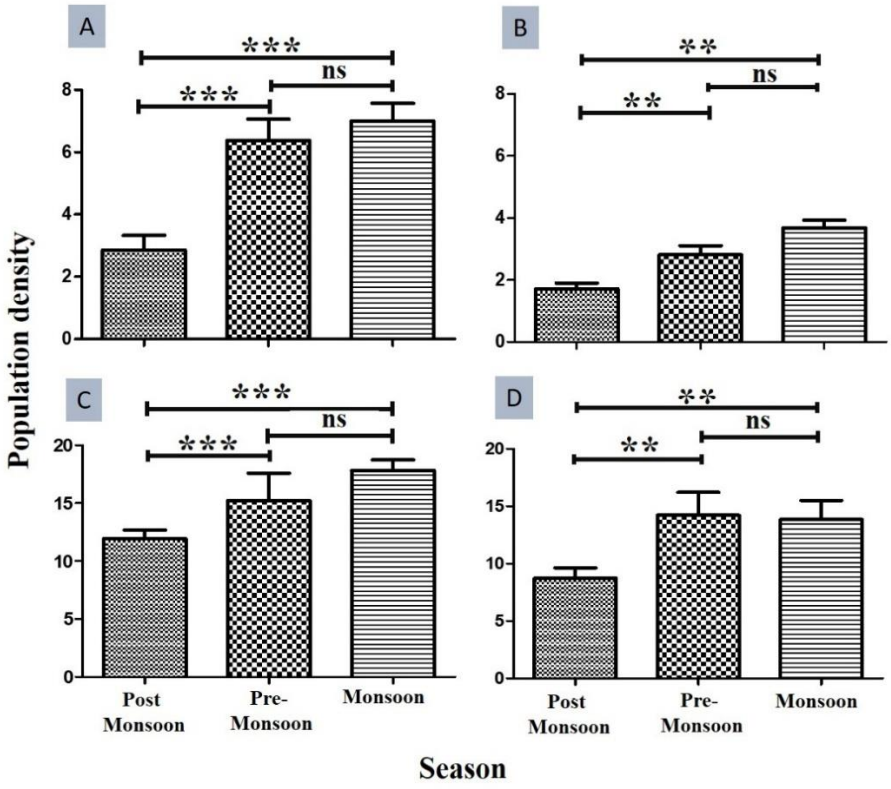


Fig. 19: Analysis of variance showing seasonal variation of Other microarthropods. Panels (A) and (B) represent Other microarthropods in litter for NF and PF, respectively, while panels (C) and (D) represent Other microarthropods in soil for NF and PF, respectively.

Total microarthropods

Monthly population density of Total microarthropods in NF and PF.

The graph **(Fig. 20)** illustrates the monthly variation in total microarthropod abundance in litter and soil for NF and PF. In NF litter, populations peaked in July (30.95×10^2 m^{-2}) and August (32.14×10^2 m^{-2}), followed by a gradual decline from September (30.15×10^2 m^{-2}) to the lowest levels during winter months—December (7.25×10^2 m^{-2}), January (5.91×10^2 m^{-2}), and February (11.98×10^2 m^{-2}). In PF litter, populations increased from April (8.51×10^2 m^{-2}) to summer peaks in July (12.44×10^2 m^{-2}) and August (11.77×10^2 m^{-2}), then steadily declined, reaching the minimum in December (2.94×10^2 m^{-2}) to March (3.63×10^2 m^{-2}). Overall, litter microarthropod abundance was consistently higher in NF than PF. In soil, NF exhibited a sharp peak in October (58.18×10^2 m^{-2}) and the lowest density in January (18.5×10^2 m^{-2}), whereas PF populations rose gradually to a maximum in June (44.2×10^2 m^{-2}) before declining to a minimum in January (7.55×10^2 m^{-2}).

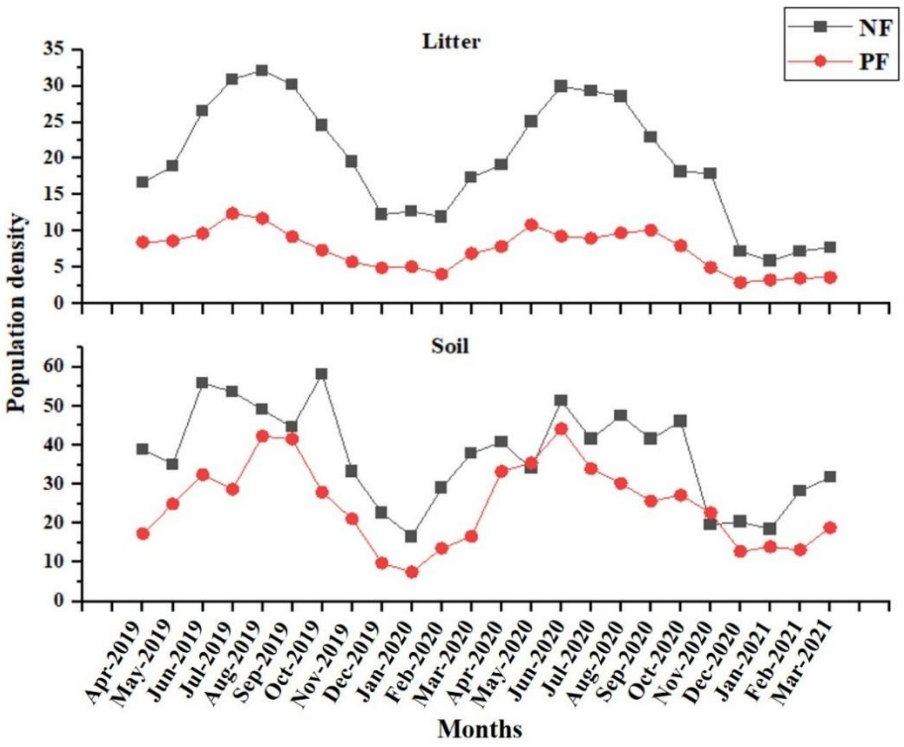


Fig. 20: Monthly fluctuation of Total microarthropods population density (Number × $10^2 m^{-2}$ in NF and PF ecosystems.

Seasonal variation of Total microarthropods in NF and PF

The figure presents ANOVA results showing seasonal variation in the population density of total microarthropods across NF and PF in both litter and soil. Panel A depicts other litter microarthropods in NF ($p < 0.0001$, $R = 0.67$), while Panel B shows other litter microarthropods in PF with significance ($p < 0.0001$, $R = 0.78$). Panel C represents other soil microarthropods NF ($p < 0.0001$, $R = 0.68$), and Panel D illustrates other soil microarthropods in PF ($p < 0.0001$, $R = 0.64$) **(Fig.21)**. In litter (Panels A and B), NF (A) shows significantly higher densities during the pre-monsoon and monsoon compared to the post-monsoon, with no significant difference between pre-monsoon and monsoon. Similarly, PF (B) exhibits a comparable trend, with significantly higher abundance in pre-monsoon and monsoon than post-monsoon, though no significant difference is observed between pre-monsoon and monsoon. In soil (Panels C and D), NF (C) also shows significantly higher densities in pre-monsoon and monsoon compared to post-monsoon, with no difference between the latter two seasons. PF (D) follows the same pattern, where microarthropod densities rise significantly from post-monsoon to pre-monsoon and monsoon, but do not differ between pre-monsoon and monsoon. Overall, the analysis highlights strong seasonal effects, with pre-monsoon and monsoon supporting greater microarthropod populations in both forest types and habitats, while post-monsoon consistently shows the lowest densities.

In the present study, a total population density of 896.21×10^2 m^{-2} and 595.36×10^2 m^{-2} was recorded from soil in natural forest (NF) and plantation forest (PF), respectively, while litter supported 473.44×10^2 m^{-2} and 178.01×10^2 m^{-2} in NF and PF. Among the identified groups, Acarina dominated, followed by Collembola, whereas the "Other" category, being a composite of multiple taxa, exhibited the highest overall abundance. These results are in line with previous studies that consistently report higher population densities and species diversity of microarthropods during the wet or monsoon season compared to the dry or cold months. For example, Bini et al., (2016) observed that both diversity and evenness of microarthropods reached their maximum in the wet season in rubber plantations of South Kerala. Similarly, Syed et al., (2023) reported peak densities of soil-dwelling microarthropods during the monsoon season, while the lowest occurred in the post-monsoon period in forest ecosystems of South Assam. Callejas-Chavero et al., (2015)

also demonstrated that microarthropod diversity was markedly higher during the rainy season than in the dry or cold months of the year. Earlier works further strengthen this pattern. Chitrapati and Singh, (2007) documented the maximum population density of soil microarthropods during the monsoon, while Doulo, (2007) recorded higher species diversity in rainy months compared to winter in natural and degraded forests of Lumami, Nagaland. In agreement, Kumar et al., (2023) reported that soil animal group density and species association were greatest in the monsoon season, followed by post-monsoon and summer

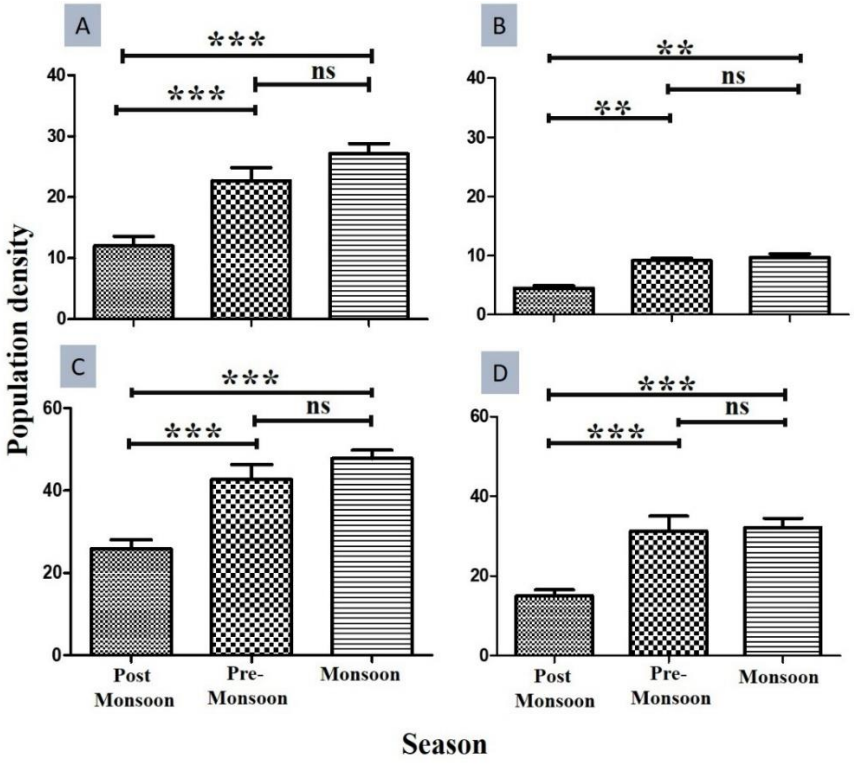


Fig. 21: Analysis of variance showing seasonal variation of Total microarthropods. Panels (A) and (B) represent Total microarthropods in litter for NF and PF, respectively, while Panels (C) and (D) represent Total microarthropods in soil for NF and PF, respectively.

Community analysis of Litter and Soil microarthropods

In the present investigation a total of $896.21\times10^{2}m^{-2}$ and $595.36\times10^{2}m^{-2}$ were recorded in soil from NF and PF respectively. Whereas from litter a total of 473.44 $\times10^{2}m^{-2}$and $178.01\times10^{2}m^{-2}$ were recorded from NF and PF respectively. Since microarthropods were categorized into three major groups: Acarina, Collembola, and

Others. The Other group, comprising diverse taxa, naturally exhibited higher overall population density due to the inclusion of multiple taxa. However, when examined at the level of specific order, Acarina showed higher population density among soil microarthropods, followed by Collembola.

Comparison of litter and soil microarthropods in NF and PF

The table **(Table 4**) presents the seasonal population density of microarthropods in NF and PF highlighting clear differences between the two forest types. In NF, Acarina dominate across seasons, followed by Collembola and Others, all showing increase from post-monsoon to monsoon. In PF, total abundance is comparatively lower, with $4.52\times10^{2}m^{-2}$ in the post-monsoon, $9.16\times10^{2}m^{-2}$ in the pre-monsoon, and $9.72\times10^{2}m^{-2}$ in the monsoon, resulting in a cumulative total of $23.4\times10^{2}m^{-2}$. Overall, the data indicate that NF supports a richer and more diverse microarthropod community compared to PF, with both forests showing a clear seasonal pattern of lowest populations in the post-monsoon and highest during the monsoon, reflecting the influence of favorable warm and moist conditions.

Seasonal shifts show more contribution of population density in monsoon season. Overall, NF is characterized by higher dominance compared to PF. The table also presents the seasonal percentage contribution of microarthropod groups in NF and PF. In NF, Acarina consistently dominate, contributing 41.68–46.64% across seasons, followed by Collembola (30.33–31.94%) and Others (23.67–27.99%. In PF, however, the distribution is more balanced. Acarina (31.48%–35.26%) and Collembola (27.88–33.95%) contribute similarly, while the Others group makes share (30.68%–37.83%). The dominance of Oribatid mites and Collembola observed in our study aligns with previous research, which has consistently highlighted these groups as major contributors to total soil microarthropod communities across different habitats and conditions. According to Das, (2021), soil microarthropods were most abundant in forest land and least abundant in rubber plantation land, with Oribatid mites contributing 32 percent to the total community, followed by Collembola with 24 percent. In a similar study, Tsurho and Ao, (2014b) found that Collembola made up 26.27 percent of the total soil microarthropod population in forest ecosystems, while in jhum lands their contribution increased to 34.37 percent. Seasonal variations were also evident, as highlighted by Kaur and Dhingra, (2017), who reported that in Punjab

the abundance of astigmatic mites reached 55.25 percent during the rainy season, declined to 31.12 percent in summer, and was lowest in winter at 13.63 percent. Pator and Ray, (2022) further observed that Collembola accounted for 28.33 percent and Oribatid mites for 25.78 percent, together representing nearly half of the total population sampled throughout the year, while Hymenoptera contributed 13.66 percent, Mesostigmatid mites 10.52 percent, and Prostigmatid mites 5.87 percent. Supporting these findings, Sánchez-Galindo et al., (2021) recorded Oribatida at 53.7 percent and Collembola at 25.3 percent of the total microarthropods. More recently, Rodríguez-Pajares et al., (2025) identified 14 soil microarthropod taxa, with mites (Acari) contributing the largest share at 44 percent, followed by Hymenoptera at 34 percent and springtails (Collembola) at 15 percent, while all other taxa together contributed less than 2 percent of the total community.

Table 4. NF and PF seasonal population density in Litter (Numbers ± S.E × 10 ^{2} m^{-2} and percentage) (In parenthesis contribution to respective seasons)

NF	**Population density (Numbers ± S.E × 10 ^{2} m^{-2})**			
Season	**Acarina**	**Collembola**	**Others**	**Total**
Post Monsoon	5.59±0.84	3.69± 0.67	2.84±0.48	12.01±1.57
	(46.64)	***(30.75)***	***(23.67)***	***(19.41)***
Pre-Monsoon	9.47±0.97	6.89±0.73	6.36±0.53	22.72±1.64
	(41.68)	***(30.33)***	***(27.99)***	***(36.75)***
Monsoon	11.45±0.74	8.66±0.57	6.99±0.51	27.11±1.50
	(42.24)	***(31.94)***	***(25.78)***	***(43.85)***
PF	**Population density (Numbers ± S.E × 10 ^{2} m^{-2})**			
Season	**Acarina**	**Collembola**	**Others**	**Total**
Post Monsoon	1.55±0.19	1.26±0.13	1.71±0.19	4.52±0.39
	(34.29)	***(27.88)***	***(37.83)***	***(19.32)***
Pre-Monsoon	3.23±0.22	3.11±0.28	2.81±0.22	9.16±0.33
	(35.26)	***(33.95)***	***(30.68)***	***(39.15)***
Monsoon	3.06±0.27	2.96±0.30	3.64±0.24	9.72±0.54
	(31.48)	***(30.45)***	(***37.45)***	***(41.54)***

The table **(Table 5)** presents the seasonal population density of soil microarthropods in NF and PF. In NF, microarthropod abundance is consistently high, with the total population increasing from $25.8\times10^2m^{-2}$ in the post-monsoon to $42.67\times10^2m^{-2}$ in the pre-monsoon, and peaking at $47.77\times10^2m^{-2}$ during the monsoon, giving a cumulative value of $116.24\times10^2m^{-2}$. Among groups, Acarina and others shows more population in all seasons. In PF, overall densities are comparatively lower, with the total increasing from $15.01\times10^2m^{-2}$ in the post-monsoon to $31.27\times10^2m^{-2}$ in the pre-monsoon, and slightly higher at $32.18\times10^2m^{-2}$ in the monsoon. Here too, Acarina and others gives stronger contribution while Collembola remain least abundant. Overall, NF supports a much richer and more stable soil microarthropod community than PF, with both forests showing a strong seasonal trend of lowest densities in the post-monsoon and highest in the monsoon. The table also shows the seasonal percentage contribution of different microarthropod groups in NF and PF. In both the sites, Acarina and Other groups contribute more compared to Collembola.

Table 5: NF and PF seasonal population density in Soil (Numbers ± S.E × 10^2 m^{-2} and percentage) (In parenthesis contribution to respective seasons)

NF	**Population density (Numbers ± S.E × 10^2 m^{-2})**			
Season	**Acarina**	**Collembola**	**Others**	**Total**
Post Monsoon	8.38±1.19 ***(32.48)***	5.53±0.94 ***(21.43)***	11.91±0.75 ***(46.16)***	25.80±2.28 ***(22.20)***
Pre-Monsoon	15.55±1.07 ***(36.44)***	11.87±0.78 ***(27.82)***	15.21±1.82 ***(35.65)***	42.67±2.83 ***(36.71)***
Monsoon	17.30±1.30 ***(36.22)***	12.62±0.75 ***(26.42)***	17.81±0.80 ***(37.28)***	47.77±1.83 ***(41.10)***
PF	**Population density (Numbers ± S.E × 10^2 m^{-2})**			
Season	**Acarina**	**Collembola**	**Others**	**Total**
Post Monsoon	4.69±0.57 ***(31.25)***	1.58±0.39 ***(10.53)***	8.74±0.88 ***(58.23)***	15.01±1.51 ***(19.13)***
Pre-Monsoon	10.04±1.60 ***(32.11)***	7.03±0.61 ***(22.48)***	14.20±1.54 ***(45.41)***	31.27±2.91 ***(39.85)***
Monsoon	12.20±0.99 ***(37.91)***	6.12±0.39 ***(19.02)***	13.85±1.47 ***(43.04)***	*32.18±2.05* ***(41.01)***

The table following table (**Table 6**) compares the population density of litter and soil microarthropods (expressed as numbers ± S.E. × 10^2 m^{-2}) between NF and PF. In the NF, microarthropod abundance is higher overall, particularly in the soil (896.21 ± 0.58) compared to the litter (473.44 ± 1.70). Within groups, Acarina are most abundant in the litter (204.49 ± 8.03), while in the soil they are also highly represented (315.61 ± 2.33). Collembola follow, with 146.30 ± 0.61 in litter and 227.63 ± 0.23 in soil. The Others group (which includes diverse taxa) is the most dominant in soil (352.97 ± 0.22). In contrast, the PF shows much lower total densities in both litter (178.01 ± 2.50) and soil (595.36 ± 2.15), highlighting reduced habitat quality or resource availability compared to NF. Among groups, Acarina are still the most abundant in both litter (59.43 ± 1.13) and soil (204.85 ± 0.94) than Collembolla.

Table 6: Population density of litter and soil microarthropods (Numbers ± S.E.) × 10^2 m^{-2})

Microarthropod group	Population density (Numbers ± S.E × 10^2 m^{-2})			
	NF		PF	
	Litter	Soil	Litter	Soil
Acarina	204.49±8.03	315.61±2.33	59.43±1.13	204.85±0.94
Collembola	146.30±0.61	227.63±0.23	55.13±0.87	107.00±0.58
Others	122.65±0.50	352.97±0.22	63.45±0.89	283.51±0.95
Total	473.44±1.70	896.21±0.58	178.01±2.50	595.36±2.15

Community analysis of litter microarthropods

Table 7 presents the seasonal variation in microarthropod species diversity in litter between NF and PF, showing consistently higher diversity values in NF across all seasons. In NF, Margalef's richness index (Da) ranged from 9.87 to 10.65, indicating higher species richness compared to PF, where values were lower (5.61–6.26). Similarly, the diversity index (H') was higher in NF (3.80–3.97) than PF (3.13–3.25), while maximum diversity (Hmax') values were also slightly higher in NF (4.06–4.12) than PF (3.36–3.40). Evenness was high and fairly consistent in both forests, ranging from 0.93 to 0.96 in NF and 0.92 to 0.96 in PF, suggesting a relatively uniform distribution of individuals among species. Overall, NF supported greater richness and diversity of microarthropods, while both forest types showed stable evenness across

seasons. In the present study, the Shannon-Wiener diversity values obtained align well with earlier research on soil microarthropods across different habitats and management systems. For instance, Roy et al., (2020), working on oribatid mites in tea agro-ecosystems of Assam, observed the highest diversity in organic gardens (H′ 3.08), followed by biorational (2.80) and conventional gardens (2.72), highlighting the role of management intensity in structuring communities. Similarly, Bhagawati et al., (2020) reported seasonal differences in Collembola, with diversity peaking in summer (H′ = 1.48) and slightly lower values in autumn (1.43), spring (1.40), and winter (1.39); despite these variations, species richness (Simpson index = 0.72–0.86) and evenness (E = 0.83–0.92) suggested relatively stable communities year-round. Wale and Yesuf (2021) also reported that soil macro-arthropod diversity was greater in forest and grassland habitats (H′ > 2) compared to cultivated land (H′ < 2). Pielou's evenness index further indicated that soil micro-arthropods exhibited a more uniform distribution (J > 0.9) than macro-arthropods (J < 0.9). Together, these results suggest that microarthropod diversity, including Collembola and Acari, is strongly shaped by habitat type, management regime, and seasonality, with values comparable to those observed in the present study.

Table 7: Species diversity of microarthropods in litter in different seasons for NF and PF.

NF Seasons	**Margalef's Index (Da)**	**Diversity Index (H')**	**Hmax'**	**Eveness (J')**
Post Monsoon	10.65	3.88	4.12	0.94
Pre-Monsoon	9.93	3.97	4.12	0.96
Monsoon	9.87	3.80	4.06	0.93
PF Seasons	**Margalef's Index (Da)**	**Diversity Index (H')**	**Hmax'**	**Eveness (J')**
Post Monsoon	5.81	3.24	3.36	0.96
Pre-Monsoon	5.61	3.13	3.40	0.92
Monsoon	6.26	3.25	3.40	0.95

The table (**Table 8)** on soil microarthropod diversity across seasons in NF and PF shows that NF consistently supports higher richness and diversity compared to PF, with slight seasonal variations. In NF, Margalef's index (Da) ranged from 6.04 in pre-

monsoon to 6.55 in post-monsoon, indicating relatively stable but slightly higher richness after the monsoon. Similarly, the diversity index (H') remained high across seasons (3.37–3.43), with the highest value in pre-monsoon. Maximum diversity (Hmax') was stable at 3.46 across all seasons, while evenness was also consistently high (0.97–0.98), indicating an even distribution of individuals. In PF, species richness (Da) showed a small seasonal rise from 5.02 in pre-monsoon to 5.48 in monsoon, while diversity (H') decreased from 3.10 in post-monsoon to 2.98 in monsoon. Hmax' remained constant at 3.17, whereas evenness (J') was high (0.97) during post- and pre-monsoon but declined to 0.93 in monsoon, suggesting a slight dominance of certain groups in that season. Dey and Hazra (2021) also reported that diversity indices varied across sites, with study site 1 showing higher species diversity during the post-monsoon season, while the other three sites recorded greater diversity during the monsoon. Overall, NF maintained higher and more stable diversity across seasons, while PF exhibited lower diversity with a modest seasonal decline in monsoon.

Table 8: Species diversity of microarthropods in Soil in different seasons for NF and PF.

NF Seasons	**Margalef's Index (Da)**	**Diversity Index (H')**	**Hmax'**	**Eveness (J')**
Post Monsoon	6.55	3.39	3.46	0.97
Pre-Monsoon	6.04	3.43	3.46	0.98
Monsoon	6.53	3.37	3.46	0.97
PF Seasons	**Margalef's Index (Da)**	**Diversity Index (H')**	**Hmax'**	**Eveness (J')**
Post Monsoon	5.20	3.10	3.17	0.97
Pre-Monsoon	5.02	3.08	3.17	0.97
Monsoon	5.48	2.98	3.17	0.93

The table (**Table 9**) summarizes the overall species diversity of microarthropods in litter and soil NF and PF based on different diversity indices. Margalef's Index (Da), which reflects species richness, is highest in NF litter (8.76) followed by NF soil

(5.18), and comparatively lower in PF litter (4.84) and PF soil (4.13), indicating that natural forests support a richer community than plantations, with litter harboring more species than soil. The Shannon diversity index (H') also follows a similar trend, being greatest in NF litter (3.93) and lowest in PF soil (2.97), highlighting reduced diversity in plantation habitats. The maximum diversity (Hmax') values are comparatively high in NF for both Litter and Soil. Evenness (J') is consistently high across all habitats (0.93–0.99), indicating that species are nearly evenly distributed, with PF litter (0.97) and NF soil (0.99) showing particularly balanced communities. Overall, the results demonstrate that natural forests support higher species richness and diversity compared to plantations, with litter being more diverse than soil, while community evenness remains uniformly high in both ecosystems. Cuartero et al. (2025) reported a Shannon diversity index of 3.07 for Collembola (Poduromorpha) in Switzerland, while Mohsin et al. (2022) documented comparatively lower values ranging between 2.40 and 2.47 for soil arthropod diversity in an urban forest of Dera Ghazi Khan. In line with these observations, Zheng et al. (2025) found that primary forests supported significantly higher Collembola abundance and Shannon–Wiener diversity index values than secondary forests, highlighting the strong influence of forest type on the structuring of microarthropod communities.

Table 9: Overall Species diversity of microarthropods in Litter and Soil for NF and PF.

Parameters	NF (Litter)	PF (Litter)	NF (Soil)	PF (Soil)
Margalef's Index (Da)	8.76	4.84	5.18	4.13
Diversity Index (H')	3.93	3.30	3.42	2.97
Hmax'	4.13	3.40	3.47	3.18
Eveness (J')	0.95	0.97	0.99	0.93

The table **(Table 10**) presents the average faunal resemblance (%) of total microarthropods in litter and soil across different seasons in NF and PF. In the litter habitat, resemblance between the two forest types was moderately high, ranging from 73.38% in the post-monsoon to 75.86% during the monsoon, with the highest

similarity recorded in the monsoon season, indicating that microarthropod communities in litter become more alike during periods of higher rainfall. In contrast, the soil habitat showed a much higher resemblance, with values of 87.5% in both post-monsoon and pre-monsoon seasons, and peaking at 97.5% during the monsoon. This suggests that soil microarthropod assemblages are more stable and similar between the two forests than litter microarthropods, and that seasonal influence, especially the monsoon, enhances community resemblance in both habitats, with soil showing stronger convergence than litter.

Table 10: Community similarity of total microarthropods in Litter and Soil habitat.

Habitat	Season	Average fauna resemblance (%)
Total microarthropods in Litter	Post Monsoon	73.38
	Pre-Monsoon	74.19
	Monsson	75.86
Total microarthropods in Soil	Post Monsoon	87.5
	Pre-Monsoon	87.5
	Monsson	97.5

COLLEMBOLA

1. ***Callyntrura vestita***

2. ***Callyntrura semiviolacea***

3. ***Dicranocentrus*** **sp.**

4. Acanthurella satkosiaensis

5. Lepidocyrtus sp.(a)

6. Seira sp.

7. Lepidocyrtus heterolepis

8. Lepidocyrtus sp. (b)

9. Lepidocyrtus himalayanus

10. Alloscopus sp.

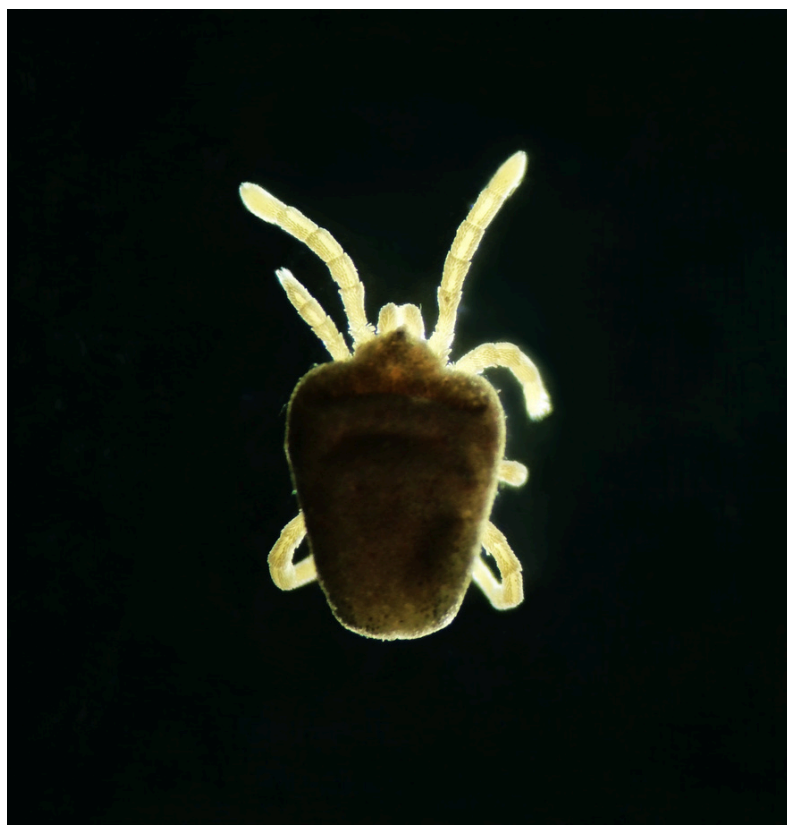
11. Onychiuridae

12. Hypogastriridae

13. Bourletiellidae

14. Neanuridae

ACARI



1. Trombidiidae (a)

2. Trombidiidae (b)

3. *Leptus* sp.

4. Bdellidae

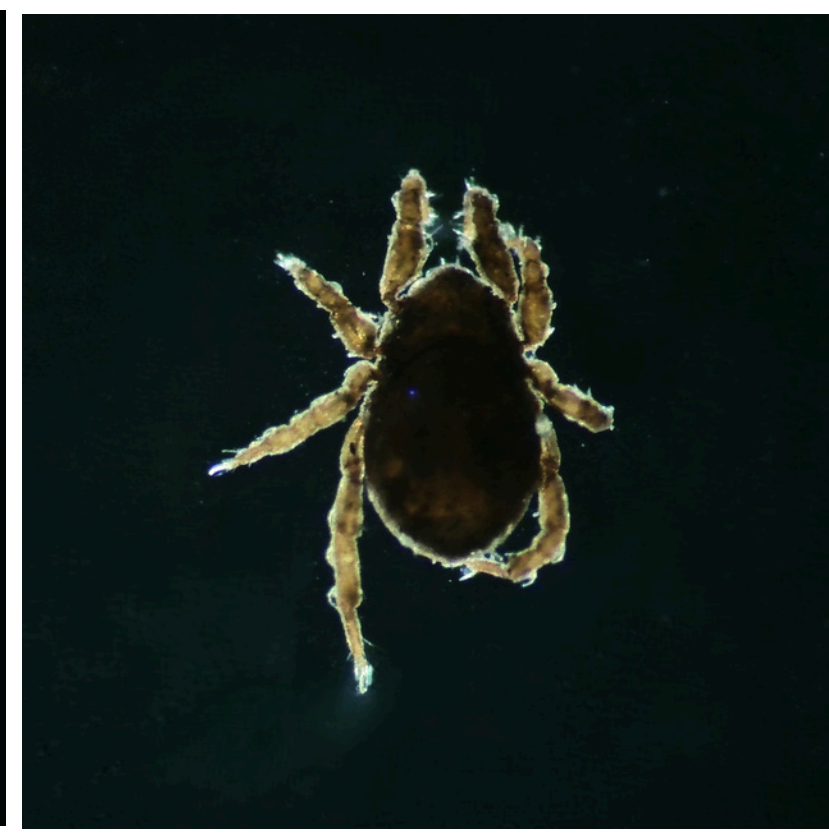
5. Laelapidae (a)

6. *Tydeus* sp.

7. Dinychidae

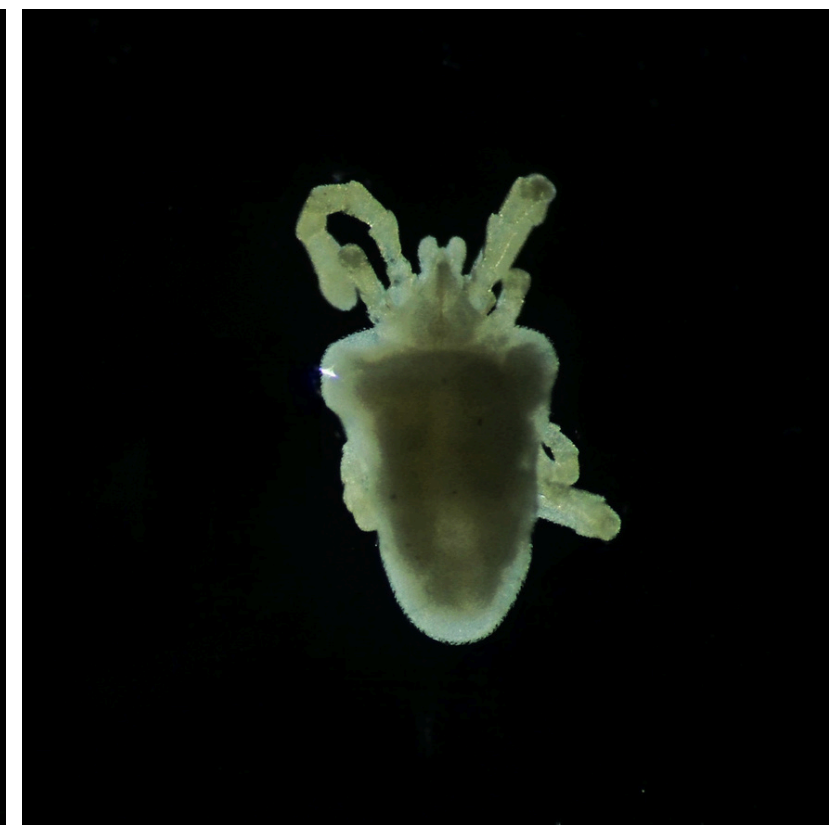
8. *Microtrombidium* sp.

9. *Macrocheles sp*

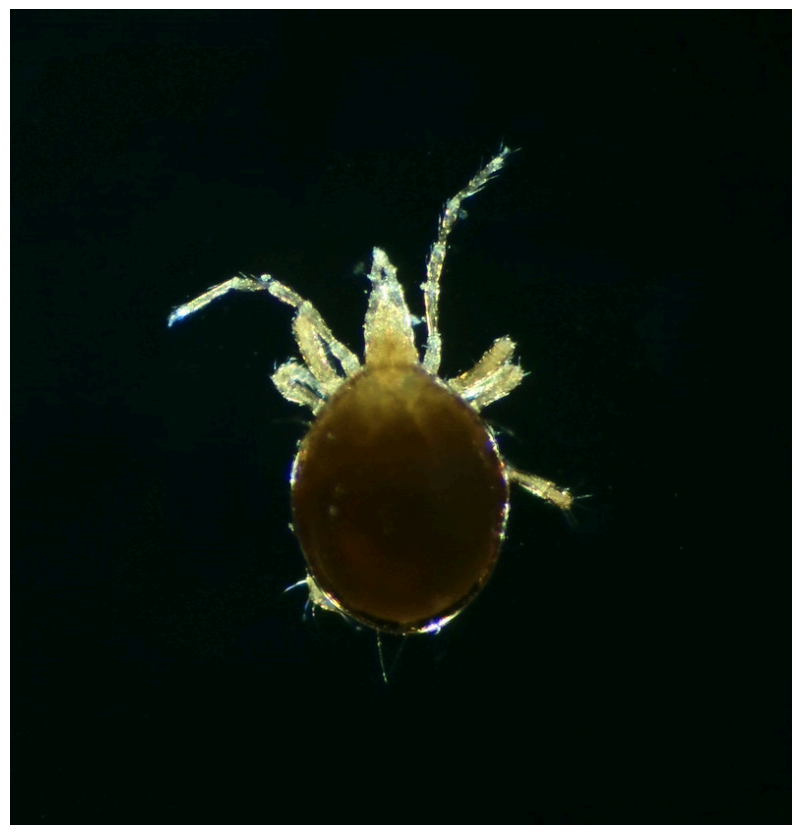


10. *Jacotella ornata*

11. Trombidiformes (a)



12. Trombidiformes (b)

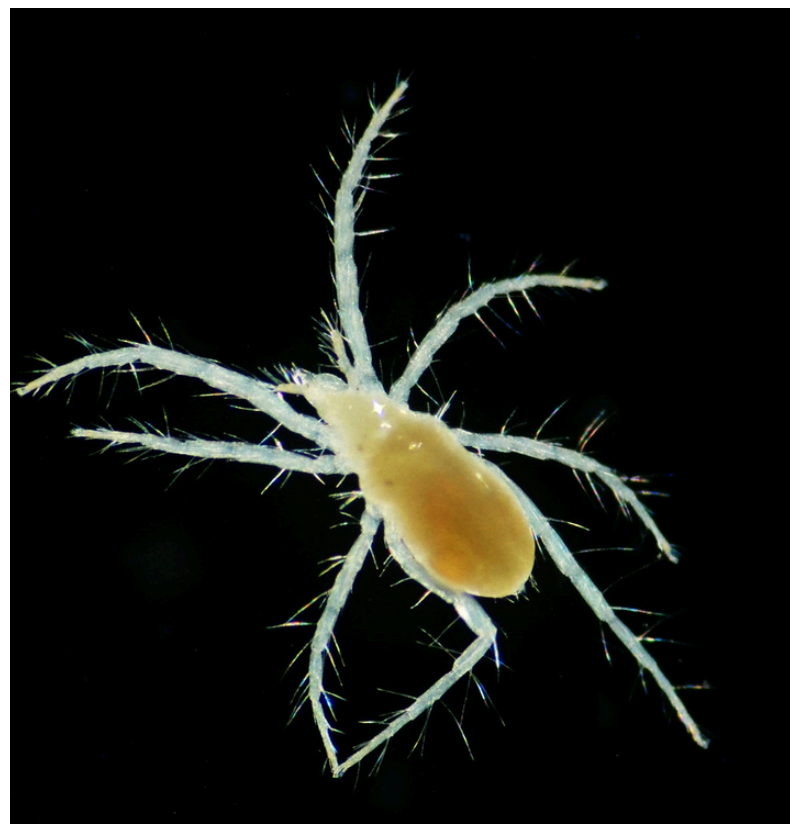


13. Laelapidae (b)

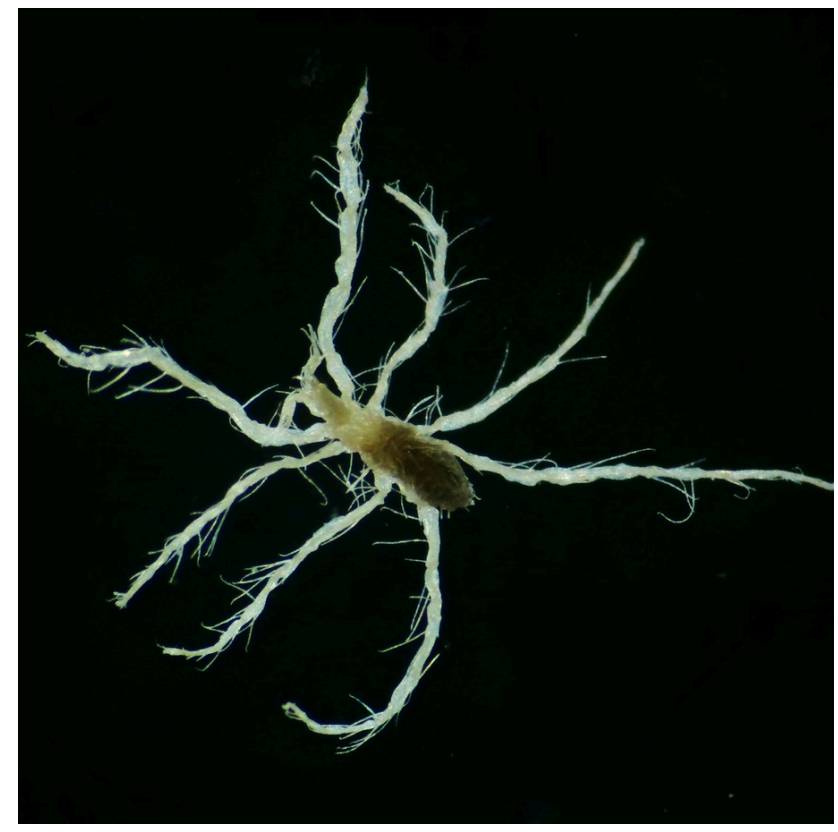
14. Mesostigmata

15. *Urodiaspis* sp.

16. Trombidiformes (c)



17. Rhagidiidae (a)



18. Rhagidiidae (b)

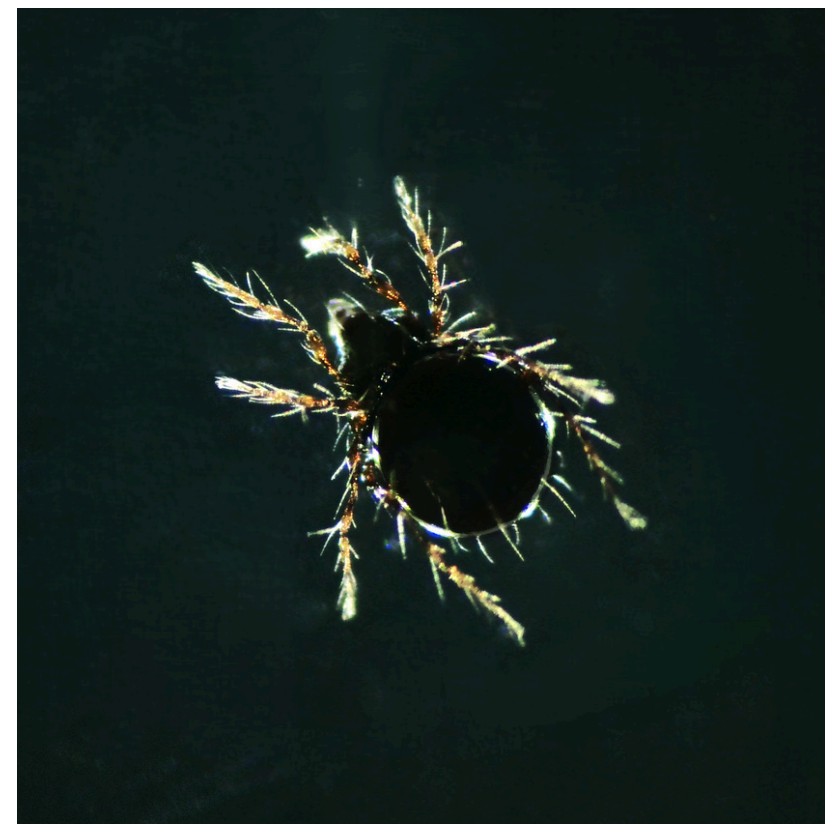
19. *Lepidacarus ornatissimus*

20. Erythracaridae

21. *Galumna flabellifera*

22 . Scheloribatidae

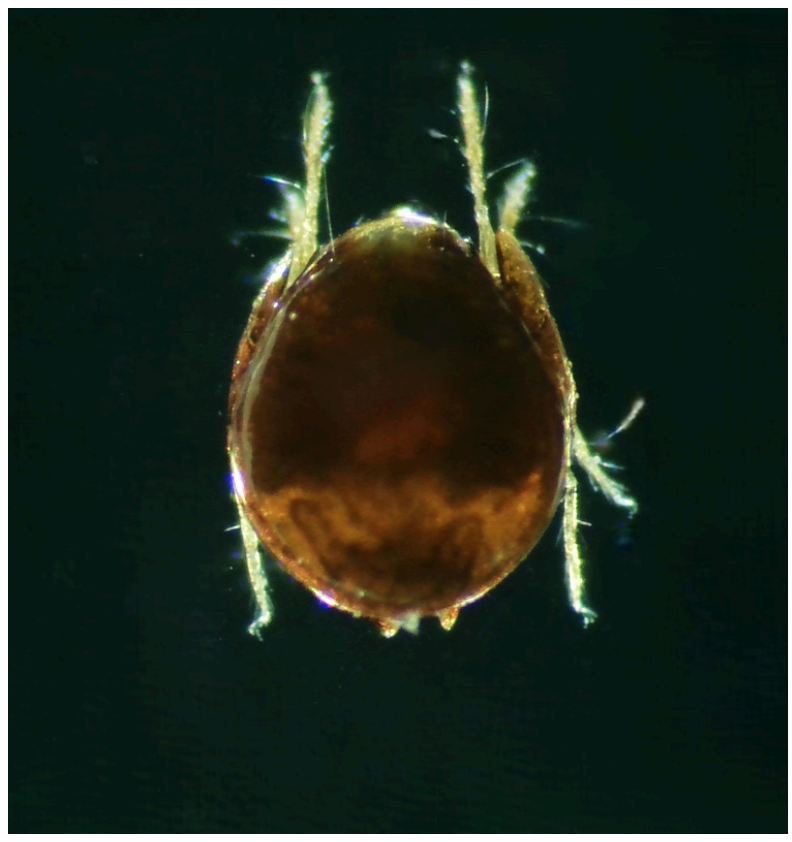
23. Phthiracaridae.



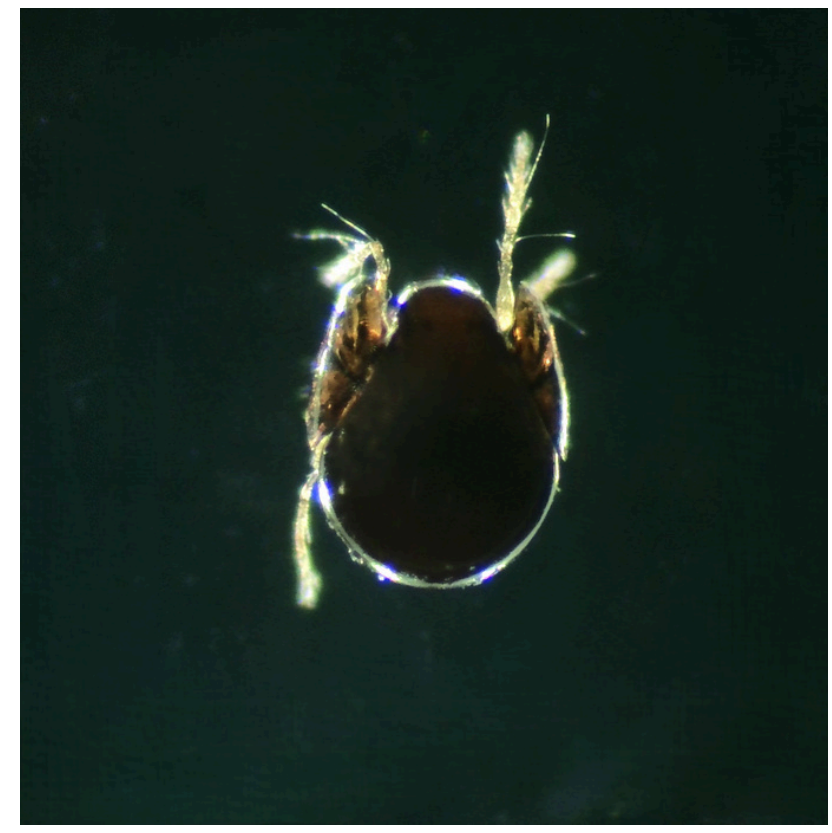
24. *Arcoppia dendropectinata*

25. *Trichotocepheus erabuensis*

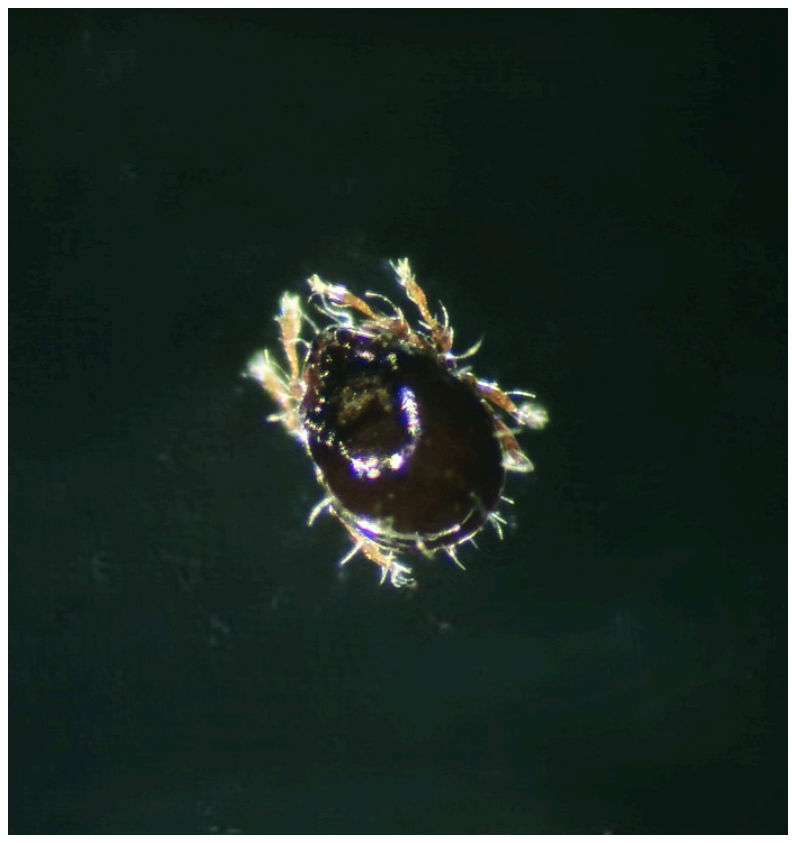
26. *Allothrombium* sp.



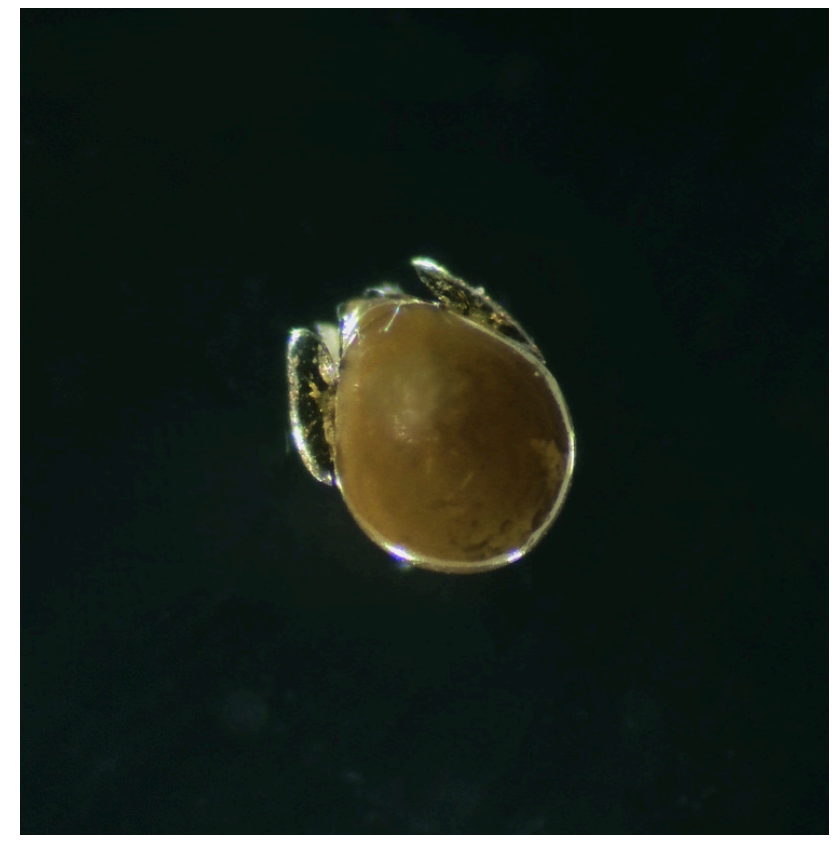
27. Galumnidae



28. *Carinogalumna clericata*

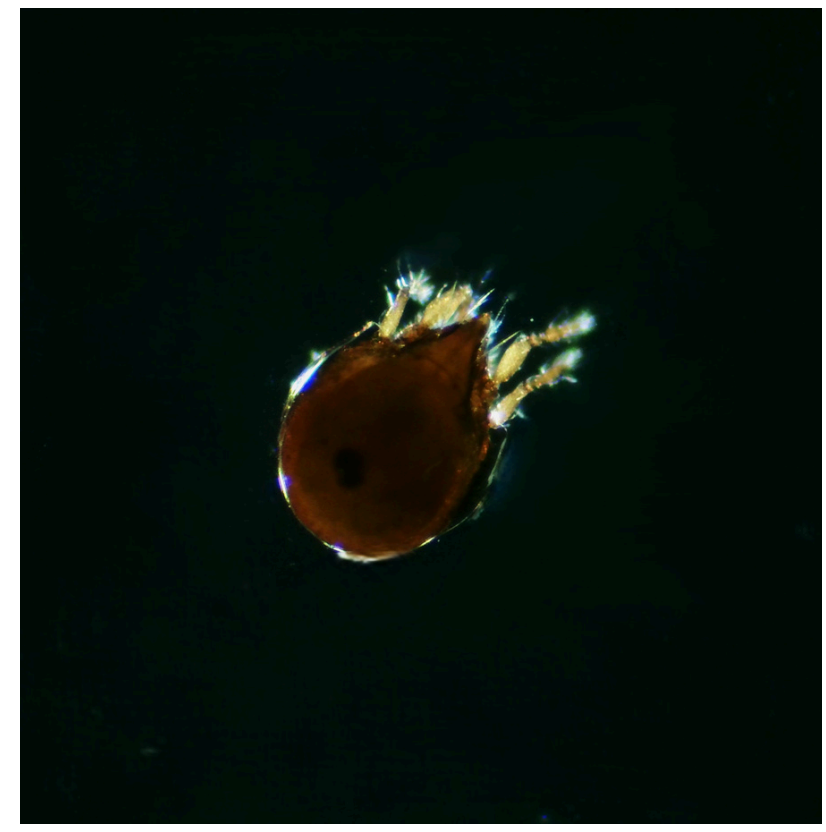


29. *Rimachensis*



30. *Galumna flabellifera*

31. ***Urobovella*** **sp**



32. ***Pergalumna (P.) brasiliensis***

33. ***Tetranychus***

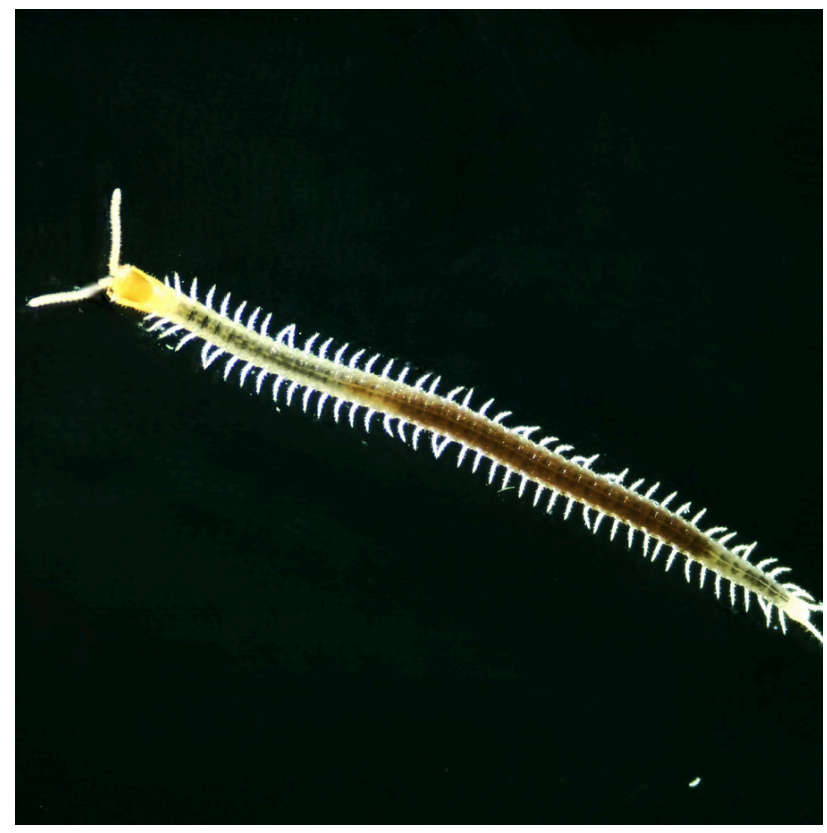
34.Trombidiformes (d)

OTHERS

1. Coleoptera

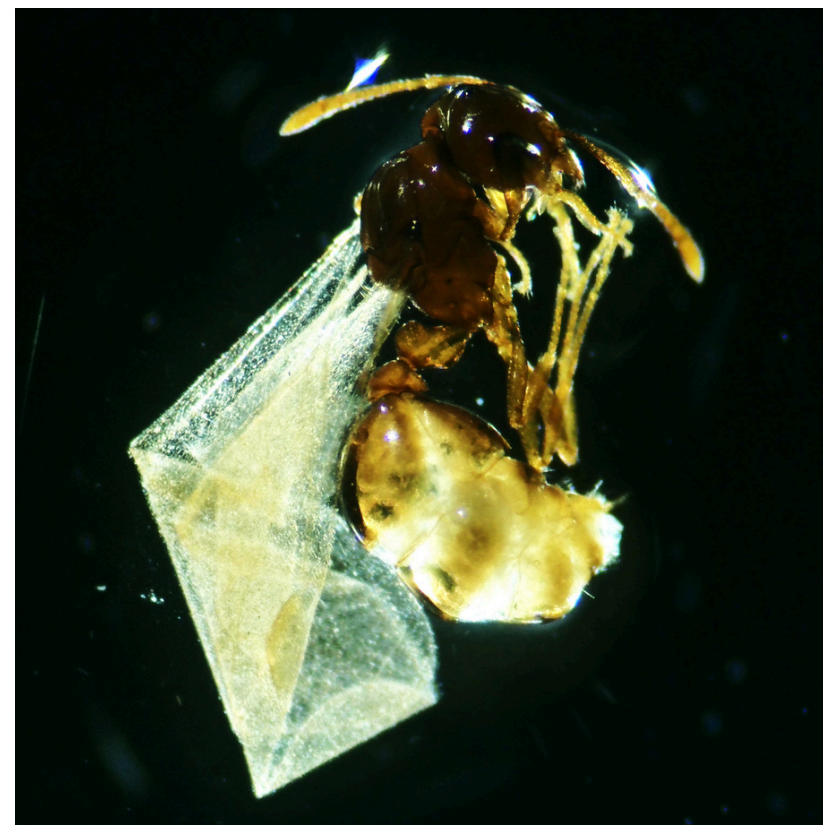
2. Arachnida

3. Diplopoda



4. Chilopoda

5. Diplura



6. Hymenoptera

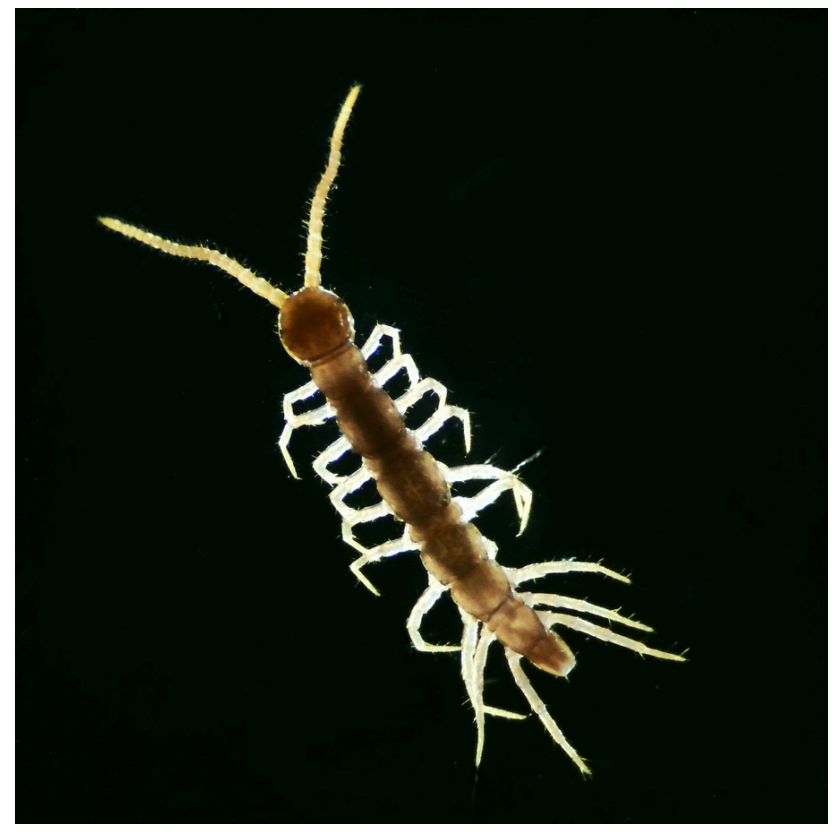
7. Coleoptera

8. Isopoda

9. Arachnida

10. Coleoptera

11. Symphyla



12. Chilopoda

13. Diplura

14. Araneae

Litter decomposition is governed by complex abiotic–biotic interactions that regulate nutrient cycling and ecosystem functioning (Batzorig et al., 2023). Among abiotic factors, soil properties play a fundamental role in organic matter breakdown, as moisture, temperature, pH, and nutrient availability strongly control microbial activity and faunal abundance, thereby shaping decomposition rates that often fluctuate with seasonal and diurnal climatic variability (Zhang and Wang, 2015; Xu et al., 2015; Broadbent et al., 2017). Soil texture, bulk density, and other edaphic properties significantly influence litter decomposition and carbon retention (Hairiah et al., 2006), while soil temperature and moisture are critical in altering organic matter decomposition and nutrient mineralization, with temperature regulating metabolic rates of decomposers and moisture controlling soluble substrate availability and microbial activity (Riggs et al., 2015; Petraglia et al., 2018; Mukherjee et al., 2019; Liu et al., 2022; Tan et al., 2020). Seasonal increases in soil temperature can further enhance nitrogen mineralization by stimulating microbial processes and accelerating organic matter breakdown (Lu and Xu, 2014). In parallel, aboveground plant traits, particularly species composition and litter chemistry, strongly affect decomposition dynamics by influencing microbial colonization and enzymatic activity (Epps et al., 2007; Bourget et al., 2023). These abiotic and litter-driven influences, soil fauna, especially microarthropods, are critical biological regulators of decomposition. Incorporating soil fauna in decomposition models improves predictive accuracy by up to 77%, while their exclusion significantly reduces litter breakdown across tropical, subtropical, and temperate forests (Wall et al., 2008; Zan et al., 2022). Microarthropods operate at two functional levels: as litter transformers, they fragment plant residues, enhance microbial colonization, and stimulate nutrient release, while as ecosystem engineers, they restructure soil and influence microbial dispersal (Filser, 2002; Culliney, 2013; David, 2014). Groups such as Collembola and Acari promote nitrogen mineralization, soil respiration, and dissolved organic carbon dynamics through interactions with litter and microbes, while also mediating indirect effects on plant health via soil organic matter decomposition, nutrient cycling, and pathogen suppression (Patoine et al., 2017; Neher and Barbercheck, 2019; Jernigan et al., 2022). Functioning as decomposers, bacterivores, fungivores, and carnivores, soil microarthropods are integral to organic matter cycling, with more than 50% of net primary production entering soils through litter inputs that they help transform (Cebrian, 1999; Caurtero et al., 2025). Their abundance and diversity are strongly

regulated by soil conditions, vegetation type, and climate, and they also serve as sensitive bioindicators of soil health, responding to changes in organic matter, moisture, temperature, and even pollution (Peck et al., 2005; Das et al., 2010; Yee et al., 2025). Collectively, the interactions among soil properties, litter characteristics, and soil microarthropods shape the rates and pathways of decomposition, underpinning nutrient cycling, ecosystem resilience, and recovery under environmental change (Gessner et al., 2010; Handa et al., 2014).

Soil parameters and litter decomposition.

The figure **(Fig. 22)** shows the relationships between litter mass loss (%) and soil parameters in PF (panels A, C) and NF (panels B, D). In both forest types, soil temperature (ST) exhibited a significant positive correlation with mass loss (PF: R^2 = 0.355, p = 0.002; NF: R^2 = 0.311, p = 0.004), indicating its regulatory role in decomposition. Soil organic carbon (OC) was more strongly correlated in NF (R^2 = 0.605, p < 0.0001) compared to PF (R^2 = 0.343, p = 0.002), suggesting that organic matter plays a greater role in natural forests. Soil pH also showed significant correlations in both sites (PF: R^2 = 0.546; NF: R^2 = 0.278). Regarding nutrient dynamics, N was significantly linked to mass loss in both PF (R^2 = 0.266, p = 0.009) and NF (R^2 = 0.397, p = 0.001), with a stronger effect in NF. Potassium (K) and moisture content (MC) also showed strong positive associations, particularly in NF (K: R^2 = 0.456; MC: R^2 = 0.511, both highly significant). Phosphorus (P) showed weaker relationships overall, with no significant effect in PF (R^2 = 0.105, p = 0.121) but a clear positive role in NF (R^2 = 0.354, p = 0.002). In our study, the overall moisture content and organic carbon levels in the NF were consistently higher than in the PF, indicating more favorable conditions for decomposition. Litter decomposition is regulated by multiple abiotic factors, including vegetation type, litter quality, microclimate, and soil nutrient content (Bakker et al., 2011; Freschet et al., 2012). With the exception of phosphorus in PF, all measured soil parameters (pH, moisture content, carbon, nitrogen, and potassium) showed a positive correlation with mass loss in both PF and NF, underscoring the role of soil properties in decomposition. Previous studies have shown similar patterns; for instance, Petraglia et al., (2019) demonstrated that interactions between litter quality and soil moisture affect mass loss, while soil temperature and moisture together influence the decomposition constant (*k*). Likewise, Tan et al., (2020) emphasized that soil moisture regulates microbial activity and substrate availability, and Akpor et al., (2006) highlighted that organic matter sustains

soil macroorganism populations critical for litter mixing and decomposition. Supporting these findings, Wang et al., (2020) reported that soil physicochemical properties positively influence decomposition in high-alpine environments, and Liu et al., (2021) found that leaf decomposition rates increase with rising soil moisture. Moreover, forest nutrient status strongly determines decomposition dynamics; according to Dent et al., (2006), mass loss and nutrient release are fastest in nutrient-rich alluvial forests and slowest in nutrient-poor heath forests.

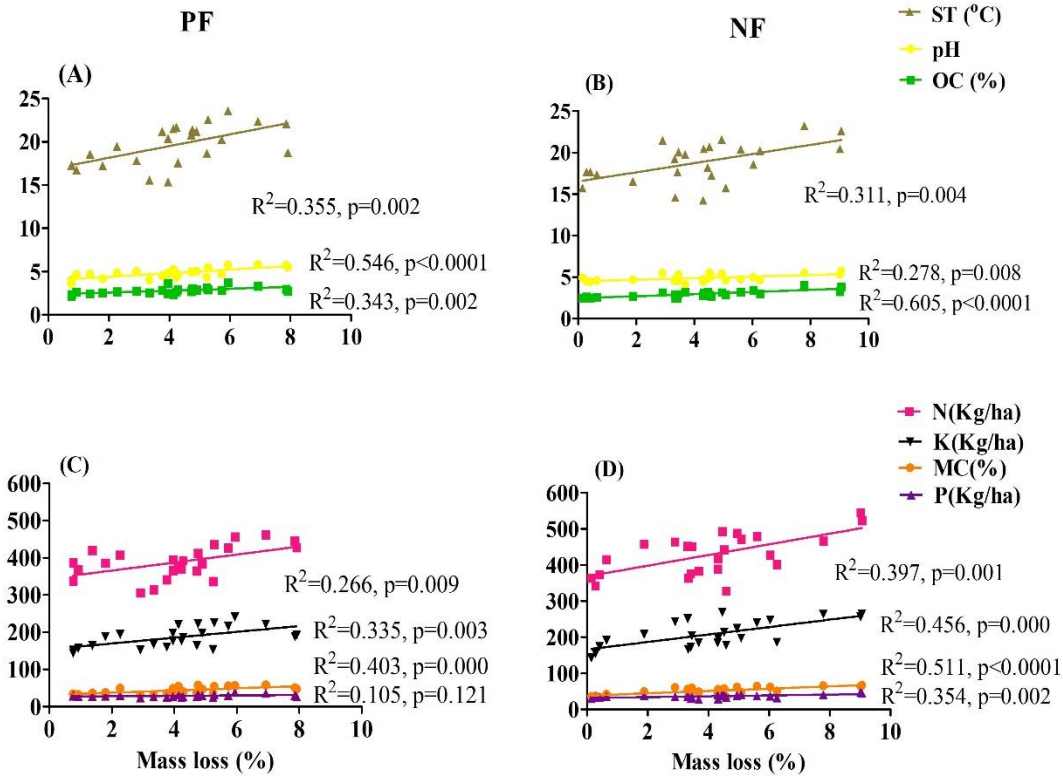


Fig. 22: Pearson correlation coefficients (R) and p-values (P) demonstrate the relationships between soil parameters and litter mass loss at two distinct study sites. Panels A and C display soil parameters for PF, while Panels B and D represent NF. With the exception of phosphorus in the PF, all soil parameters exhibit statistically significant correlations with litter mass loss ($p < 0.05$).

Litter dynamics and decomposition

The regression analysis was conducted to examine the relationship between litter mass loss and various litter parameters, such as carbon, lignin, N, P, K revealed significant results. The graph **(Fig. 23)** depict the relationship between litter mass loss (%) and the concentration of various litter parameters (Carbon, Lignin, Nitrogen, Phosphorus, and Potassium) in two forest types: PF and NF. Panels (A) and (B) show

that as mass loss increases, both lignin and carbon concentrations rise with lignin exhibiting a stronger correlation (higher R^2) in both forests, particularly in PF (R^2=0.665 for lignin vs. R^2=0.585 for carbon, PF). Panels (C) and (D) indicate that N, P, K concentrations also increase with mass loss, with nitrogen showing the strongest correlation in both forest types (R^2=0.602 for PF, R^2=0.435 for NF). All results in the present study are statistically significant, underscoring that shifts in nutrient concentration are tightly linked to decomposition dynamics. Similarly, Ge et al., (2013) reported that litter decomposes more rapidly in nutrient-rich forests, with decomposition rates closely tied to nutrient concentrations in the litter. Early litter decomposition is generally characterized by nutrient immobilization, especially of N and P, since fresh litter often lacks adequate nutrients to sustain decomposer growth. The dynamics of soil nutrients and their regulatory influence on decomposition, however, are often indirect, as soil fertility primarily determines litter quality and availability, which in turn influences the pace of litter breakdown (Ge et al., 2013; Giweta, 2020). These insights highlight the intricate interplay between soil fertility, litter quality, and the overall decomposition process in natural ecosystems. Our linear regression analysis further confirms this linkage. In PF, nitrogen content shows the strongest relationship with litter mass loss, explaining 69.9% of the variability. Berg and McClaugherty, (2008) emphasized nitrogen as a key driver of microbial activity, thereby accelerating decomposition. Forests with higher species diversity often produce litter with a wider range of carbon (C) and nitrogen compositions, which strongly influence decomposition rates (Prescott, 2010; Lyu et al., 2023). Other nutrients such as K, C, and P also display significant, though slightly weaker, relationships with mass loss. P and K, while less influential than nitrogen, remain critical for regulating litter breakdown (Hobbie and Vitousek, 2000). In contrast, in NF, carbon emerges as the most influential factor, explaining 72.3% of the variability in litter mass loss. This observation aligns with Cleveland and Liptzin, (2007) and Craig et al., (2022), who reported that higher carbon content provides an important energy source for decomposers, leading to more efficient organic matter degradation. Beyond nutrient concentrations, the present study also demonstrates the role of abiotic factors in regulating litter decomposition. Nutrient release was found to be substantially higher in NF than in PF, highlighting the strong influence of litter quality on decomposition. During decomposition, mass loss and nutrient release are closely associated with stoichiometric ratios such C:N, and N content. Specifically,

decomposition rates tend to increase with N, P, and K concentrations, but decline with higher C:N, and lignin:N ratios (Zhang et al., 2008; Du et al., 2020). In NF, the presence of mixed litter species and plant components creates variation in initial chemical composition, which enhances decomposition efficiency (Du et al., 2020). Our findings further reveal that nitrogen content in litter was significantly higher in mixed litter (NF) compared to single-species litter (PF), underlining the central role of nitrogen in driving decomposition. Upadhyaya et al., (2012) similarly observed that plant residues richer in nitrogen decompose more rapidly, as nitrogen enhances microbial activity and accelerates organic matter breakdown. In both NF and PF, nitrogen concentrations increased during the initial stages of decomposition, a pattern also reported by Osono (2017), who observed similar trends in five subtropical plant species. This temporary increase in nitrogen may be attributed to the progressive decline of organic carbon, which elevates the relative proportion of nitrogen in litter.

Overall, the study demonstrates that litter quality, particularly nitrogen and carbon content, plays an important role in regulating decomposition dynamics providing valuable insights into nutrient cycling and ecosystem functioning across contrasting forest types.

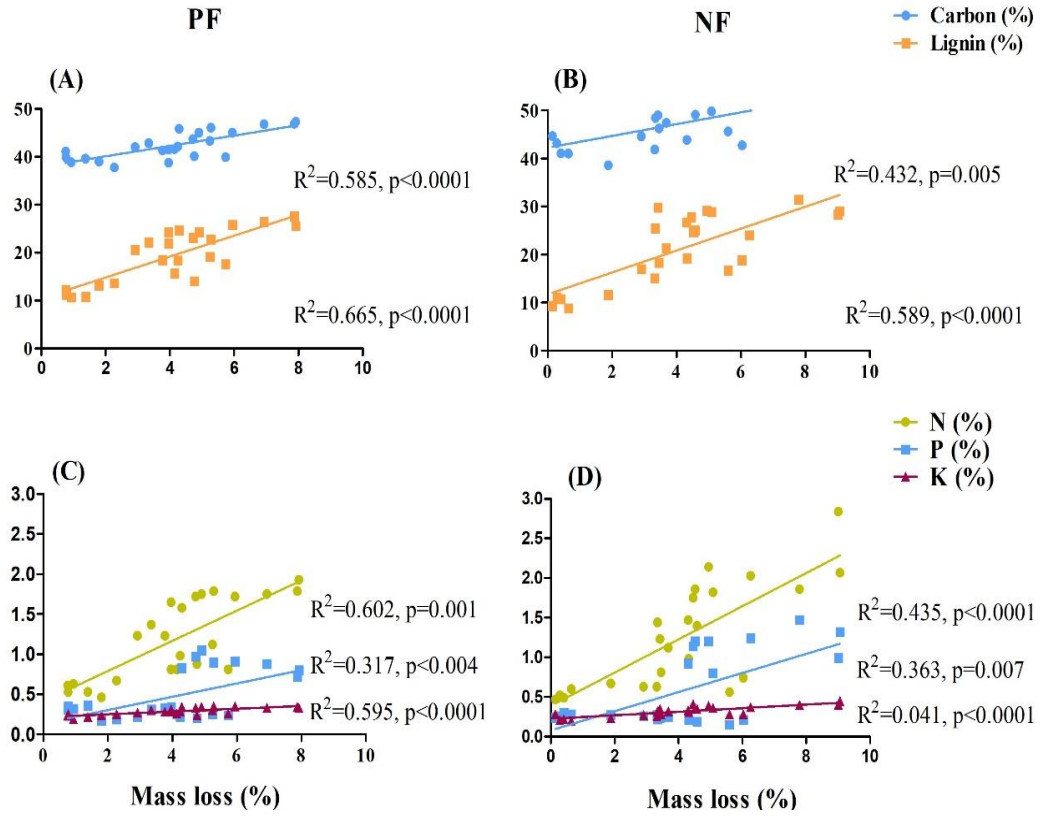


Fig. 23: Multiple regression analysis of mass loss and litter parameters, with panels (A) and (C) representing the PF, while (B) and (D) representing the NF. All litter parameters exhibit significant positive correlations with mass loss ($p<0.005$).

Litter microarthropods (Number $\times 10^2 m^{-2}$) and Mass loss (%) in NF and PF.

In the graph **(Fig. 24),** the curves of microarthropods group (Acari, Collembola, and others) against mass loss in NF show a clear seasonal synchrony**,** with all peaking during the monsoon months and dropping sharply from November–March**.** The highest mass loss (9.058%) occurs in August, closely matching the highest Acari abundance ($13.63\times10^2 m^{-2}$ in June–August) and highest Collembola value ($11.2\times10^2 m^{-2}$ in September), while the lowest mass loss (0.144%) is recorded in March, corresponding with the lowest Acari ($2.07\times10^2 m^{-2}$ in January)**,** lowest Collembola ($1.92\times10^2 m^{-2}$ in January), and lowest other microarthropods ($1.33\times10^2 m^{-2}$ in December)**.** This pattern shows that decomposition rise and fall in parallel with microarthropod populations, emphasizing their strong seasonal dependence and the key role of Acari and Collembola in driving litter breakdown. Similar trend has been seen in PF, the graph **(Fig. 25),** shows that mass loss and microarthropod populations fluctuate seasonally, with both increase in the monsoon and decline in post monsoon

(Winter). The highest mass loss (7.91% in October) coincides with relatively moderate Acari ($2.81\times10^2m^{-2}$) and other microarthropods ($2.67\times10^2m^{-2}$), while the lowest mass loss (0.76 in March) corresponds with very low Acari ($0.88\times10^2m^{-2}$ in Dec-Jan), Collembola ($0.8\times10^2m^{-2}$ in January), and others ($1.04\times10^2m^{-2}$in March). Acari reach their maximum ($4.59\times10^2m^{-2}$) in July and follow a trend similar to decomposition, while Collembola increase at a different time ($4.51\times10^2m^{-2}$ in May), showing less direct synchrony with mass loss. Other microarthropods rise steadily to a maximum ($4.74\times10^2m^{-2}$ in August), closely aligning with decomposition peaks. Overall, the curves suggest that litter decomposition is positively associated with the abundance of microarthropods, particularly Acari and "Others," although each group contributes differently across the year.

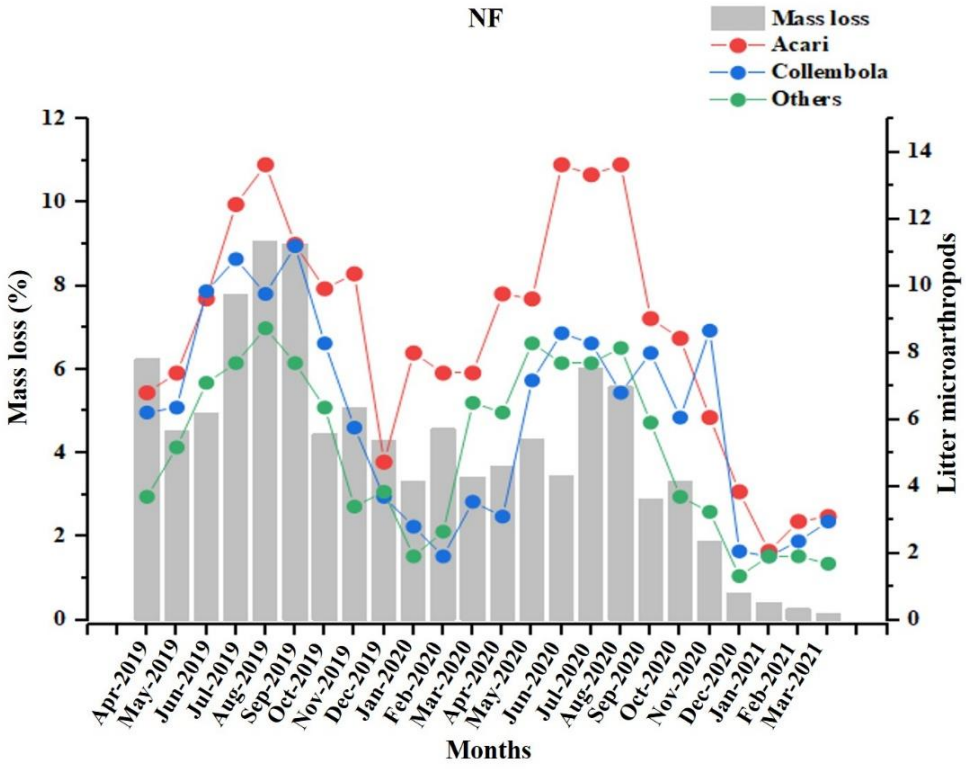


Fig. 24: Mass loss (%) with Litter microarthropods (Number$\times10^2m^{-2}$) in NF.

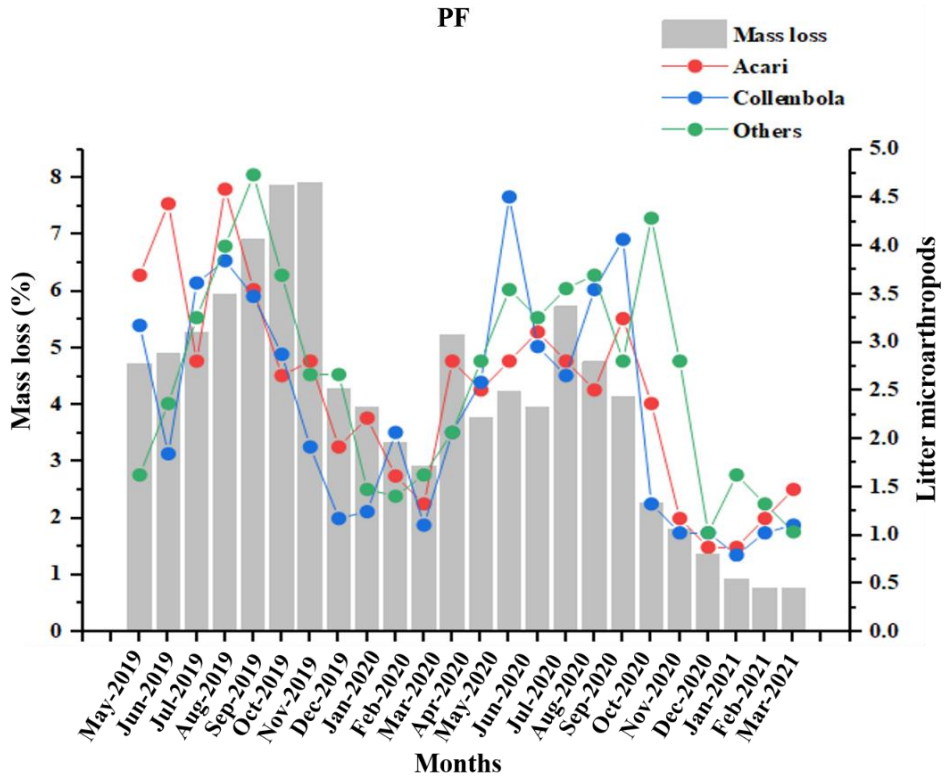


Fig. 25: Mass loss (%) with Litter microarthropods (Number $\times 10^2 m^{-2}$) in PF.

Mass loss (%) with Soil microarthropods (Number $\times 10^2 m^{-2}$) in NF and PF.

In this graph **(Fig. 26),** the three groups of microarthropods and mass loss (%) in NF show how their values change together across months, highlighting strong seasonal variation. Mass loss reaches its highest value of 9.058 in August and drops to the lowest of 0.144 in March, while Acari fluctuate widely, from a maximum of $26.51\times10^2m^{-2}$ in October to a minimum of $3.78\times10^2m^{-2}$ in December. Collembola are highest in August ($17.34\times10^2m^{-2}$) and lowest in January ($2.26\times10^2m^{-2}$)**,** whereas the "others" group ranges from $23.38\times10^2m^{-2}$ in June to $6.03\times10^2m^{-2}$ in May. The curves show that months with higher litter mass loss, such as July–September and August in particular, generally correspond with increased values of Acari, Collembola, and others, while months like December to March**,** with reduced arthropod activity, align with the lowest decomposition rates. Similarly, the graph **(Fig. 27)** shows that mass loss and the abundance of Acari, Collembola, and other microarthropods in PF vary together across months, with distinct rise in the monsoon and declines during post monsoon. The highest population of Acari ($12.87\times10^2m^{-2}$), Collembola ($9.04\times10^2m^{-2}$), and others mass loss is $21.87\times10^2m^{-2}$occurred in October, June and September respectively**,** while the lowest mass loss is $0.76\times10^2m^{-2}$ in March**,** Acari $3.78\times10^2m^{-2}$

in January, Collembola drop to zero in December and January and others $4.52\times10^{2}m^{-2}$ in January, indicating strong seasonal sensitivity. Overall, this pattern indicates that decomposition intensity is closely related to the abundance of these soil microarthropods, though each group contributes differently across the months.

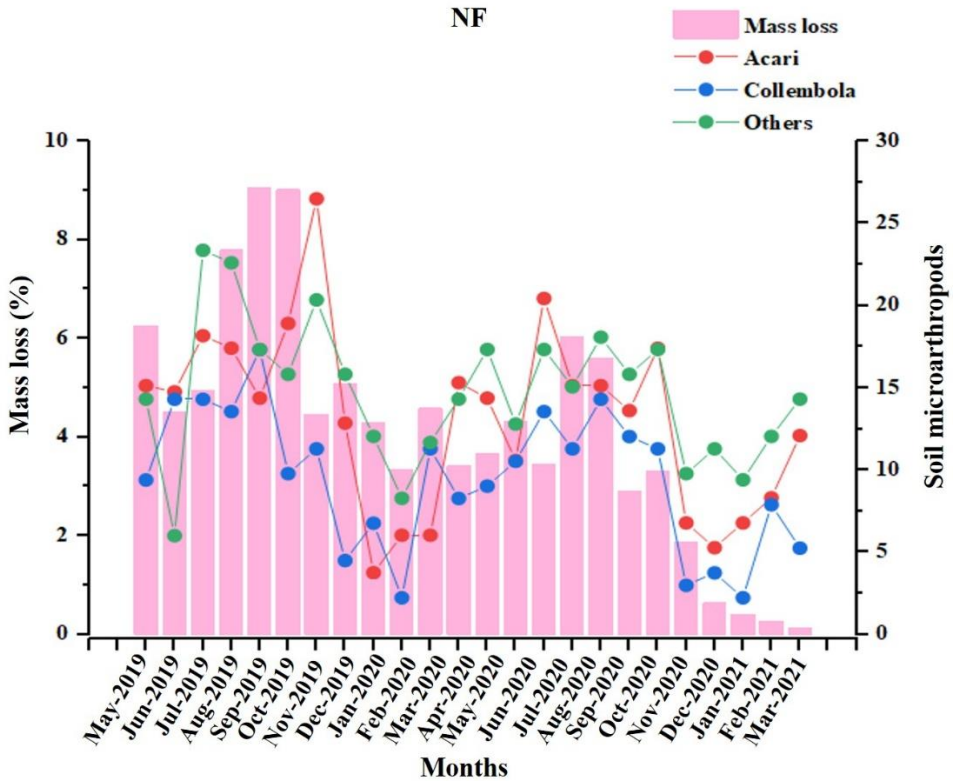


Fig. 26: **Mass loss (%) with Soil microarthropods (Number $\times10^{2}m^{-2}$) in NF.**

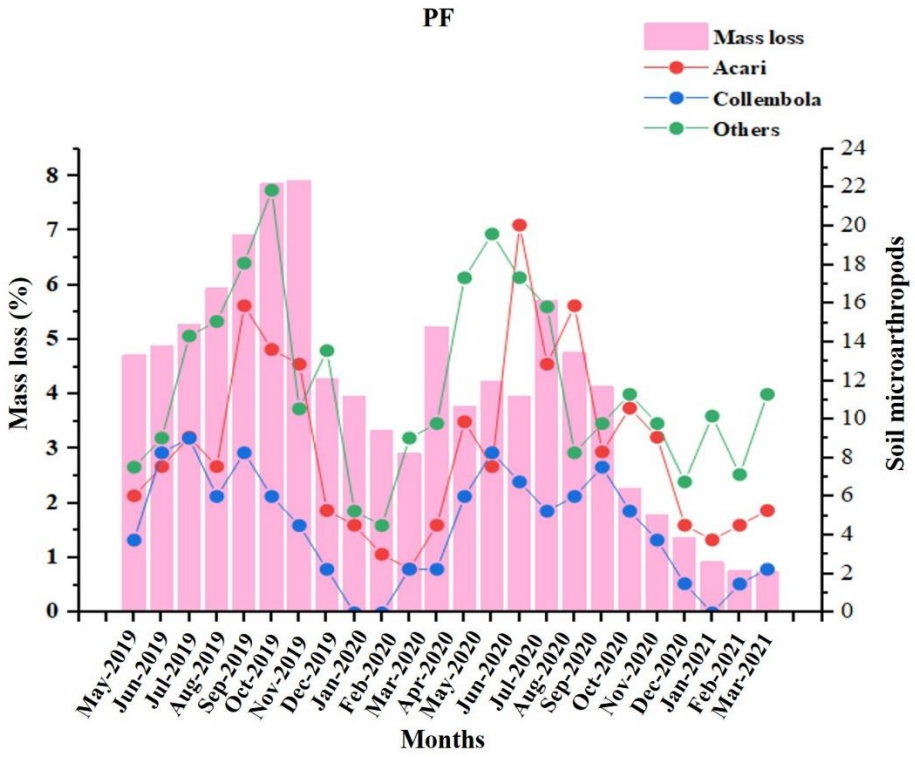


Fig. 27: Mass loss (%) with Soil microarthropods (Number $\times 10^2 m^{-2}$) in PF. Correlation between Mass loss (%) and Total microarthropods (Number $\times 10^2 m^{-2}$) of both Litter and Soil in NF and PF.

The correlation graphs **(Fig. 28)** shows that litter mass loss is positively associated with both soil and litter microarthropods in NF and PF, but the strength of the relationship differs between groups and forest types. In NF, soil microarthropods show a weaker correlation with mass loss ($R = 0.343$, $p = 0.002$), while litter microarthropods exhibit a much stronger correlation ($R = 0.622$, $p < 0.0001$), indicating their direct involvement in litter breakdown. In PF, both groups are also positively related to mass loss, with soil microarthropods showing $R = 0.347$ ($p = 0.002$) and litter microarthropods $R = 0.527$ ($p < 0.0001$), though the associations are weaker compared to NF. These results suggest that litter microarthropods play a more critical role than soil microarthropods in driving decomposition, and that their influence is stronger under the conditions of natural forest than plantation forest.

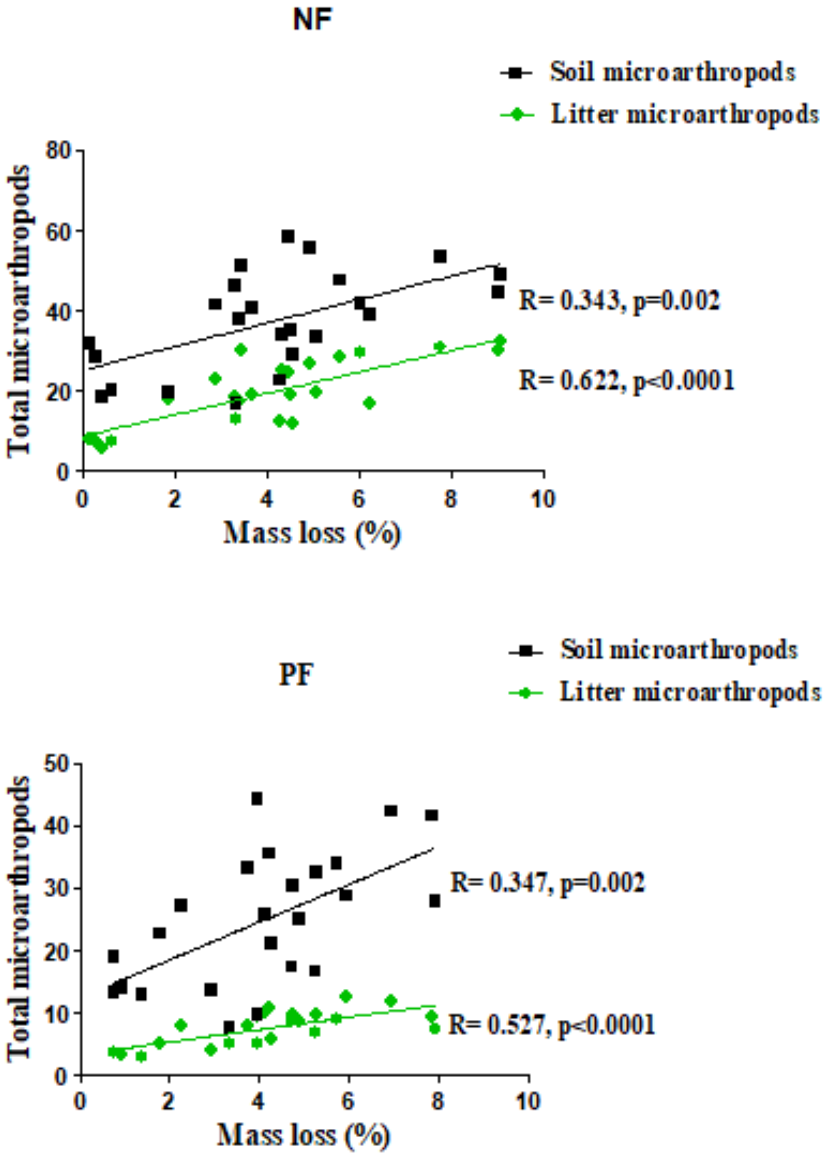


Fig. 28: Correlation between Mass loss (%) and Total microarthropods (Number $\times 10^2 m^{-2}$) of both Litter and Soil in NF and PF.

Correlation between Total Microarthropods Litter (Number $\times 10^2 m^{-2}$) with litter parameters in NF and PF.

The table **(Table 11)** shows the correlation between total microarthropods in litter with litter parameters (carbon, lignin, nitrogen, phosphorus, and potassium) in both NF and PF. In both forest types, total microarthropods showed significant positive correlations with carbon, lignin, nitrogen, and potassium, while the relationship with phosphorus was weak and not significant. In NF, potassium (K%) exhibited the

strongest correlation ($R^2 = 0.31$, $p < 0.01$), followed by lignin ($R^2 = 0.26$, $p < 0.05$). Nitrogen (N%) and carbon (C%) also showed moderate but significant correlations ($R^2 = 0.18–0.19$ and 0.16–0.17, respectively, $p < 0.05$). Similarly, in PF, total microarthropods were significantly correlated with all parameters except phosphorus, with potassium again showing the strongest correlation ($R^2 = 0.30$, $p < 0.01$). These results indicate that litter quality, particularly potassium and lignin content, plays an important role in shaping microarthropod abundance, while phosphorus availability exerts little no relation. Overall, the correlation patterns are highly consistent between NF and PF, suggesting that the relationships between microarthropods and litter chemistry are stable across forest types.

Table 11: Correlation between Total Microarthropods Litter (Number $\times 10^2 m^{-2}$) with litter parameters in NF and PF.

Sites	Pearson Correlation	Carbon (%)	Lignin (%)	N (%)	P (%)	K (%)
NF TM (Litter)	R squared	0.167	0.262	0.185	0.153	0.311
	N	24	24	24	24	24
	P value (two-tailed)	0.047	0.010	0.035	0.058	0.004
	P value summary	*	*	*	ns	**
PF TM (Litter)	R squared	0.166	0.262	0.189	0.147	0.307
	N	24	24	24	24	24
	P value (two-tailed)	0.047	0.010	0.033	0.064	0.004
	P value summary	*	*	*	ns	**

Correlation between Total Microarthropods Litter (Number $\times 10^2 m^{-2}$) with Soil parameters in NF and PF

In both NF and PF, total microarthropods in litter showed significant correlations with all measured soil parameters (pH, moisture content, organic carbon, soil temperature, nitrogen, phosphorus, and potassium), though the strength of relationships differed between sites **(Table 12).** In NF, moisture content ($R^2 = 0.870$, $p < 0.001$) and organic carbon ($R^2 = 0.689$, $p < 0.001$) emerged as the strongest drivers, followed by potassium ($R^2 = 0.649$) and nitrogen ($R^2 = 0.620$), while phosphorus showed the weakest correlation ($R^2 = 0.230$, $p < 0.05$). In contrast, PF was strongly influenced by soil temperature ($R^2 = 0.792$, $p < 0.0001$) and moisture content ($R^2 = 0.671$, $p < 0.001$), with potassium ($R^2 = 0.618$) also playing an important role; nitrogen ($R^2 = 0.296$) and phosphorus ($R^2 = 0.340$) again showed weaker correlations. Overall, both sites highlight the importance of soil moisture, organic matter, and nutrients in shaping microarthropod abundance.

Table 12: Correlation between Total Microarthropods Litter (Number $\times 10^2 m^{-2}$) with soil parameters in NF and PF

Sites	Pearson Correlation	pH	MC (%)	OC (%)	ST (°C)	N(Kg/ha)	P(Kg/ha)	K(Kg/ha)
NF TM (Litter)	R squared	0.360	0.870	0.689	0.507	0.620	0.230	0.649
	N	24	24	24	24	24	24	24
	P value (two-tailed)	0.001	P<0.001	P<0.001	P<0.001	P<0.001	0.017	P<0.001
	P value summary	**	***	***	***	***	*	***
PF TM (Litter)	R squared	0.416	0.671	0.423	0.792	0.296	0.34	0.618
	N	24	24	24	24	24	24	24
	P value (two-tailed)	0.0007	P<0.001	0.0006	P<0.001	0.006	0.002	P<0.001
	P value summary	***	***	***	***	**	**	***

Correlation between Total Microarthropods (Number $\times 10^2 m^{-2}$) in Soil (TMS) with Litter parameters in NF and PF

The table **(Table 13)** compares the correlation between total microarthropods in soil (TMS) and litter quality parameters (carbon, lignin, phosphorus, and potassium) in NF. In NF, TMS showed significant positive correlations with carbon ($R^2 = 0.269$, $p < 0.01$), lignin ($R^2 = 0.205$, $p < 0.05$), phosphorus ($R^2 = 0.207$, $p < 0.05$), and potassium ($R^2 = 0.314$, $p < 0.01$), while nitrogen showed non-significant relationship ($R^2 = 0.139$). whereas in PF none of the parameters exhibited significant correlations, with all R^2 values remaining low (0.039–0.121) and $p > 0.05$. This indicates that in NF, soil microarthropod abundance is closely linked to litter chemistry, particularly potassium and carbon, whereas in PF such relationships are absent.

Table 13: Correlation between Total Microarthropods Soil (Number $\times 10^2 m^{-2}$) with litter parameters in NF and PF.

Sites	Pearson Correlation	Carbon (%)	Lignin (%)	N (%)	P (%)	K (%)
NF TMS	R squared	0.269	0.205	0.139	0.207	0.314
	N	24	24	24	24	24
	P value (two-tailed)	0.009	0.026	0.071	0.025	0.004
	P value summary	**	*	ns	*	**
PF TMS	R squared	0.059	0.121	0.039	0.046	0.105
	N	24	24	24	24	24
	P value (two-tailed)	0.249	0.095	0.350	0.312	0.120
	P value summary	ns	ns	ns	ns	ns

Correlation between Total Microarthropods Soil (Number $\times 10^2 m^{-2}$) with Soil parameters in NF and PF

The comparison of NF and PF shows that total microarthropods in soil (TMS) were significantly correlated with most soil parameters, but the strength of associations varied between the two sites **(Table 14).** In NF, TMS showed the strongest correlations with moisture content ($R^2 = 0.620$, $p < 0.0001$), soil temperature ($R^2 = 0.534$, $p < 0.0001$), organic carbon ($R^2 = 0.523$, $p < 0.0001$), potassium ($R^2 = 0.513$, $p < 0.0001$), and pH a weaker but significant one ($R^2 = 0.254$, $p < 0.05$); while phosphorus was non-significant. In PF, similar trends were observed, with strong correlations for soil temperature ($R^2 = 0.602$, $p < 0.0001$) and moisture content ($R^2 = 0.548$, $p < 0.0001$). Unlike NF, phosphorus showed a weak but significant correlation ($R^2 = 0.167$, $p < 0.05$). Overall, both study sites show the critical role of soil moisture and temperature in regulating microarthropod abundance, though NF exhibited stronger linkages with organic carbon, moisture content, and soil temperature. These findings are in line with Wu et al., (2024), who emphasized that the taxonomic composition, abundance, and diversity indices of soil microarthropod communities are primarily governed by soil properties such as moisture, temperature, total and available K, and pH, as well as vegetation attributes including plant species richness and leaf area index. Their study further highlighted that while community composition and abundance are largely shaped by soil conditions, alpha and beta diversity are influenced by the combined and independent effects of climate, vegetation, and soil properties. Afforestation studies also provide complementary evidence. Das et al., (2010) demonstrated that afforestation of tropical laterite wastelands significantly enhanced soil biological activity, with Collembola and Acari accounting for more than 80% of the microarthropod community. Seasonal dynamics were also pronounced, with abundance peaking during the monsoon and declining in dry periods, correlating positively with soil moisture, organic carbon, and EC but negatively with temperature. These results mirror the patterns observed in NF, where higher organic carbon and favorable soil microclimate conditions promoted greater microarthropod abundance. Furthermore Yee et al., (2025), reported the bioindicator potential of soil microarthropods. Their study showed that microarthropod abundance was significantly higher in the rhizosphere of *Plantago lanceolata* ($p < 0.05$), while the Acari:Collembola ratio was shaped by the combined influence of plant identity and heavy metal contamination. Moreover, diversity patterns were highly sensitive to

aluminum and arsenic concentrations, which highlights the responsiveness of these communities to both biological and environmental stressors. This aligns with our results, where microarthropod abundance and diversity were strongly mediated by soil properties and vegetation characteristics, highlighting their value as sensitive indicators of ecosystem health.

Table 14: Correlation between Total Microarthropods Soil (Number $\times 10^2 m^{-2}$) with Soil parameters in NF and PF

Sites	Pearson Correlation	pH	MC (%)	OC (%)	ST (%)	N(Kg/ha)	P(Kg/ha)	K(Kg/ha)
NF TMS	R squared	0.254	0.620	0.523	0.534	0.413	0.097	0.513
	N	24	24	24	24	24	24	24
	P value (two-tailed)	0.0119	P<0.0001	P<0.0001	P<0.0001	0.0007	0.1366	P<0.0001
	P value summary	*	***	***	***	***	ns	***
PF TMS	R squared	0.277	0.548	0.362	0.602	0.368	0.167	0.371
	N	24	24	24	24	24	24	24
	P value (two-tailed)	0.008	P<0.0001	0.001	P<0.0001	0.001	0.046	0.001
	P value summary	**	***	**	***	**	*	**

Correlation between Total Microarthropods Litter (Number $\times 10^2 m^{-2}$) with environmental factors in NF and PF.

The relationship between total microarthropods in litter and environmental factors (relative humidity, maximum temperature, minimum temperature, and rainfall) showed broadly similar patterns in both NF and plantation forest PF, though with some differences in the strength of correlations **(Fig. 29**). In NF, microarthropod abundance was strongly and positively correlated with minimum temperature ($R = 0.767$, $p < 0.0001$), rainfall ($R = 0.765$, $p < 0.0001$), and maximum temperature ($R = 0.732$, $p < 0.0001$), indicating that warmer conditions and higher rainfall substantially increase their abundance. Relative humidity showed only a weak but significant correlation ($R = 0.199$, $p = 0.002$), suggesting it plays a comparatively minor role. In PF, the trend was similar, with significant positive correlations across all factors, but the strength of association was slightly higher for temperature, particularly minimum temperature ($R = 0.843$, $p < 0.0001$), followed by maximum temperature ($R = 0.779$, $p < 0.0001$) and rainfall ($R = 0.714$, $p < 0.0001$). Relative humidity again showed only a weak correlation ($R = 0.218$, $p = 0.002$). Overall, the results demonstrate that in both forests, temperature and rainfall are the dominant environmental drivers of litter microarthropod abundance.

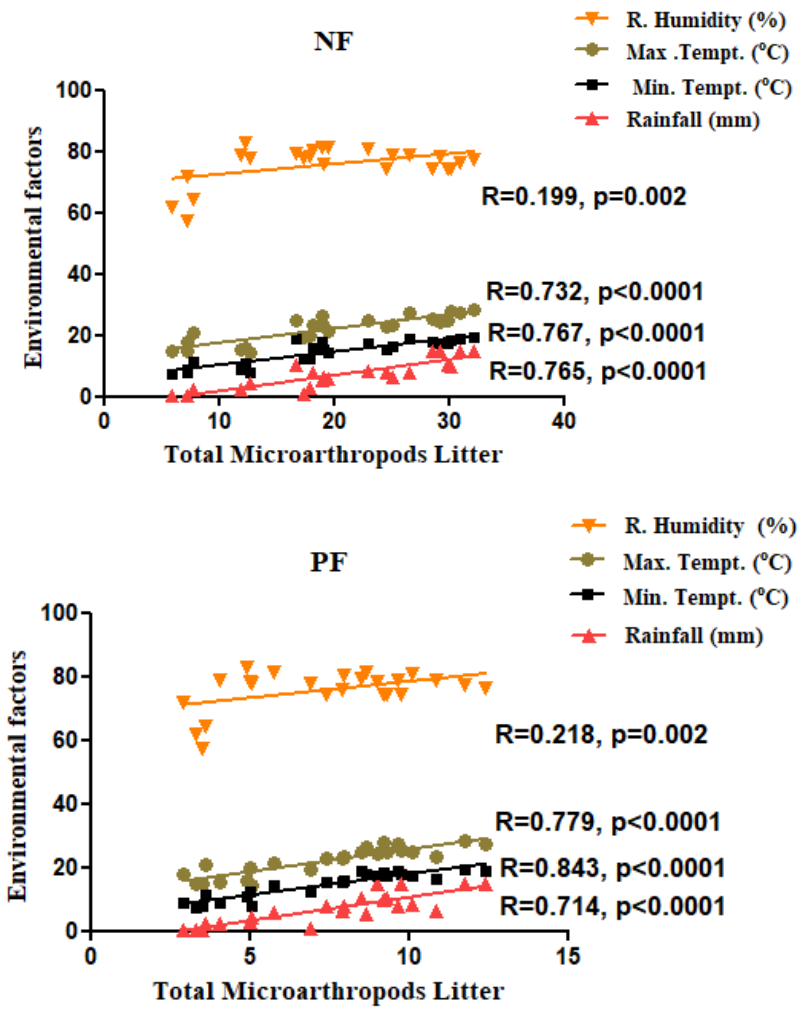


Fig. 29: Correlation between Total Microarthropods Litter (Number $\times 10^2 m^{-2}$) with environmental factors in NF and PF.

Correlation between Total Microarthropods Soil (Number $\times 10^2 m^{-2}$) with environmental factors in NF and PF.

The relationship between soil microarthropods and environmental factors (relative humidity, maximum temperature, minimum temperature, and rainfall) showed broadly similar trends NF and PF, with temperature and rainfall emerging as the dominant drivers while relative humidity played little or no role **(Fig. 30).** In NF, soil microarthropod abundance was strongly correlated with maximum temperature ($R = 0.665$, $p < 0.0001$), minimum temperature ($R = 0.664$, $p < 0.0001$), and rainfall ($R = 0.523$, $p < 0.0001$), whereas relative humidity showed non-significant ($p = 0.295$). In PF, the pattern was consistent, with maximum temperature again showing the strongest correlation ($R = 0.704$, $p < 0.0001$), followed by minimum temperature ($R = 0.634$, p

< 0.0001) and rainfall (R = 0.503, p < 0.0001); however, relative humidity showed no association (R = 0.037, p = 0.364). Overall, these results demonstrate that in both forest types, soil temperature (both maximum and minimum) and rainfall are the primary environmental regulators of soil microarthropod abundance, while relative humidity exerts no significant effect**.** Similar patterns have been documented in earlier studies. For example, Islam et al., (2018), in their investigation at Rajshahi University across five habitats (open grassland, shady grassland, crop field margin, roadside vegetation, and pondside vegetation), found that Collembola populations were positively correlated with temperature (r = 0.622, P<0.05). Their abundance also showed strong positive correlations with organic matter (r = 0.618, P>0.05) and nitrogen (r = 0.607, P>0.05). Likewise, Bhagawati et al., (2020) reported peak Collembola density during the summer season, with significant positive correlations to soil moisture and organic carbon across all seasons. Supporting this, Butterfield, (1999) observed that decomposition rates were higher in closed-canopy plantations where Collembola densities were greater compared to open sites. Klimek and Rolbiecki, (2014) showed that introducing Oribatid mites enhanced soil restoration in nursery plantations, particularly in *Betula pendula* and *Tilia cordata*, underscoring the role of mesofauna in promoting soil health and forest succession. Abbas and Parwez, (2012) also emphasized that soil temperature, moisture, pH, and food resources collectively shape microarthropod densities, with seasonal shifts driving population dynamics. Tiwari and Monika, (2024) also found significant positive correlations between Acari populations and both moisture and organic carbon content in natural (r = 0.8806) and reclaimed (r = 0.6382) forests, while Syed et al., (2023) demonstrated that soil temperature and available potassium were also positively linked with microarthropod populations. Similarly, Moitra (2017) reported positive associations between mite populations, soil moisture, and organic carbon, and Vibija and Amani, (2018) documented a strong correlation with soil temperature (r = 0.748). At a broader scale, Ma et al., (2025) highlighted that soil properties like pH, moisture, temperature, and potassium content are the primary regulators of microarthropod community composition and abundance, while alpha and beta diversity are strongly influenced by the combined and independent effects of climate, vegetation, and soil properties. This aligns with earlier observations by Peck et al., (2005), who argued that differences in microclimate and organic matter accumulation explain variations in microarthropod abundance and diversity, with natural forests supporting higher population densities

and a wider diversity of species. Importantly, Sanchez-Galindo et al., (2025) cautioned that shifts in climatic factors may pose a greater threat to oribatid mite communities in tropical montane rainforests than changes in nutrient availability, reinforcing the central role of climate-driven variables such as temperature and rainfall.

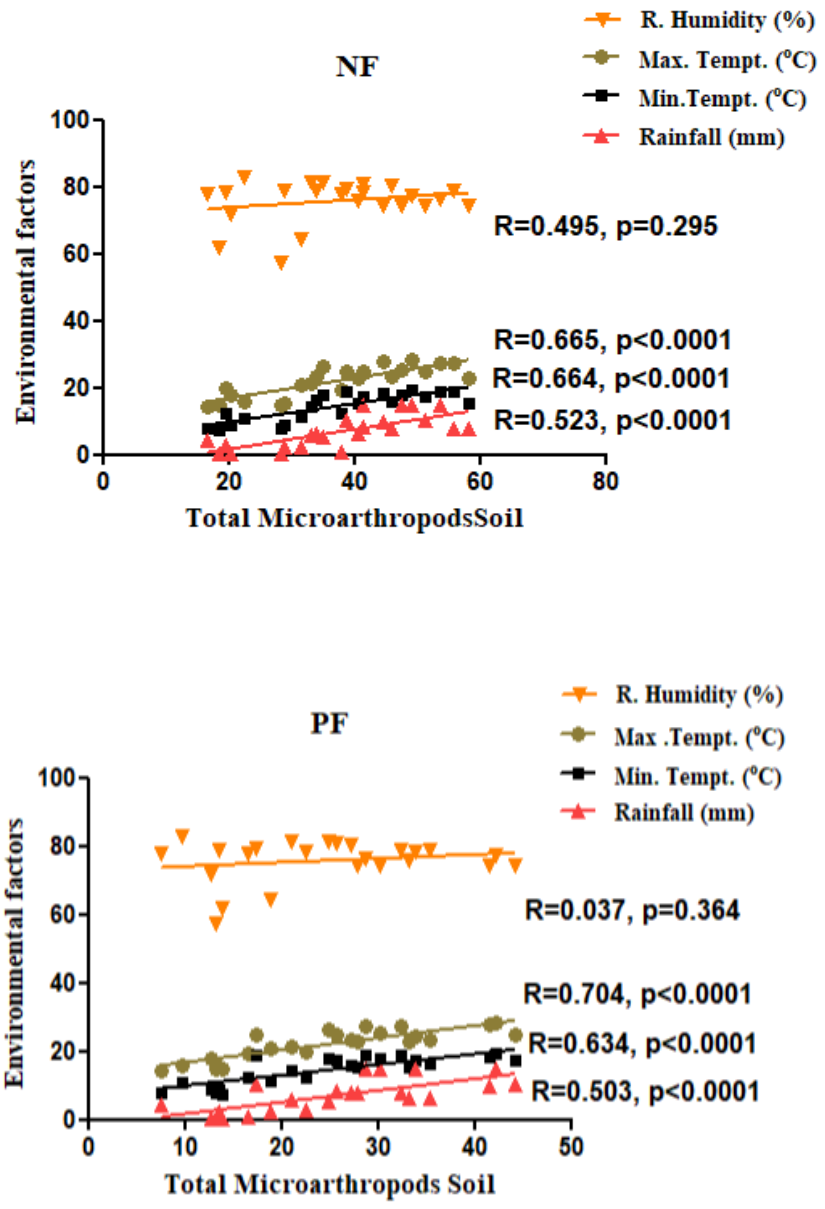


Fig. 30: Correlation between Total Microarthropods Soil (Number $\times 10^2 m^{-2}$) with environmental factors in NF and PF.

The present study was carried out in Mokokchung district, Nagaland, India, within a contiguous subtropical hill forest ecosystem. Two contrasting but adjacent forest types were selected to compare ecological processes: a natural forest (NF) and a plantation forest (PF). The NF is an old-growth stand, over 75 years of age, which has remained relatively undisturbed and supports a diverse assemblage of native flora such as *Molineria capitulata, Pavetta indica, Itea macrophylla, Ficus hirta, Trema orientalis, Musa flaviflora, Percicaria wallichii, Pilea trinervia, Oplismenus hirtellus,* and others, thereby contributing to high structural complexity and ecosystem integrity. In contrast, the PF is a managed monoculture stand of *Duabanga grandiflora* approximately 25 years old, planted at regular spacing (~7 ft), resulting in a relatively uniform canopy and reduced understory vegetation. The juxtaposition of these two forests provided an opportunity to compare natural versus managed systems under the same regional climatic regime.

The climate of the study area is characterized as subtropical to warm temperate, with distinct seasonal variation. Three major seasons were distinguished: the post-monsoon, pre-monsoon and monsoon. During the two-year study period, annual average rainfall was approximately 1942 mm, with the majority falling during the monsoon months. Temperature and humidity also followed seasonal patterns: mean maximum temperatures ranged from 14.65°C in January to 26.95°C in August, while mean minimum temperatures ranged from 7.7°C in January to 18.61°C in July. Relative humidity remained consistently high (69.6–80.1%) and peaked during the monsoon, particularly in May and July. These climatic conditions provided a strong seasonal framework that influenced soil properties, litter decomposition, and decomposer communities across both forest types.

Soil parameters showed marked differences between the two forest types as well as clear seasonal fluctuations. Soil temperature followed the ambient climate, being highest during the monsoon and lowest in winter, with PF consistently exhibiting slightly higher soil temperatures than NF due to its more open canopy and reduced shading. Soil pH was acidic in both sites, but NF maintained a more stable pH range, whereas PF showed stronger seasonal fluctuations. Organic carbon content and soil moisture were significantly higher in NF, especially during the monsoon, reflecting the denser canopy, thicker litter layer, and greater organic matter inputs that enhance water retention. Similarly, macronutrients (N, P, K) showed strong seasonal trends,

peaking during the monsoon when microbial and faunal activity was high, and declining during the post-monsoon. Across all seasons, NF maintained higher nutrient concentrations than PF, likely due to greater litter diversity and more complex nutrient cycling processes.

Litter decomposition was strongly influenced by these seasonal patterns. Decomposition rates were fastest during the monsoon, when warm temperatures, high soil moisture, and abundant microbial activity created favorable conditions for organic matter breakdown. NF exhibited a higher decomposition constant (k = 0.007 day^{-1}) compared to PF (k = 0.005 day^{-1}), indicating that litter in NF decomposed more rapidly and efficiently. This difference can be attributed to higher litter quality, greater nutrient availability, and richer decomposer communities in NF. However, overall mass loss patterns showed a similar seasonal rhythm in both sites, highlighting the dominant role of climate in regulating decomposition. Nutrient concentrations in decomposing litter, particularly C, N, P, and K, declined steadily over time, with NF litter consistently retaining higher nutrient levels. Lignin, usually considered a recalcitrant compound, also showed interesting seasonal dynamics: during the monsoon, lignin content correlated positively with mass loss, suggesting that favorable microclimatic conditions promoted microbial degradation of complex organic matter.

Soil microarthropods formed a critical component of the decomposition process and showed marked differences between the two forest types. Across the study, 34 species of Acarina and 14 species of Collembola were identified, alongside other groups such as Myriapoda, Araneae, and Hymenoptera. Both abundance and diversity were consistently higher in NF compared to PF, reflecting the greater habitat complexity and resource heterogeneity in the natural system. Seasonal variation was pronounced, with populations lowest during the post-monsoon, increasing in the pre-monsoon, and peaking during the monsoon, coinciding with favorable temperature and moisture conditions. Overall, total populations in the natural forest, markedly higher, with 896.21 ± 0.58 ×10² m^{-2} recorded in soil and 473.44 ± 1.70 ×10² m^{-2} in litter, compared to the plantation forest (595.36 ± 2.15 ×10² m^{-2} in soil and 178.01 ± 2.50 ×10² m^{-2} in litter). This clear difference reflects the greater habitat complexity and resource availability in NF, which supports richer and more abundant soil faunal communities than the relatively simplified PF system. Diversity indices confirmed this

trend: Margalef's richness and Shannon-Wiener diversity were significantly higher in NF, whereas evenness showed no marked difference. Group-wise analysis further revealed that in Acari dominates Collembola in both litter and soil microarthropods in NF. ANOVA confirmed that seasonal effects were highly significant ($p < 0.05$), with strongest peaks during the monsoon. Taken together, the findings clearly demonstrate that litter decomposition and nutrient cycling in this subtropical hill forest are primarily governed by seasonal climatic variation but are strongly modulated by forest type. The NF, with its higher soil nutrient status, greater organic matter content, richer litter diversity, and more complex microarthropod community, consistently outperformed PF in terms of decomposition rates and nutrient turnover. These results emphasize that natural forests maintain stronger ecological resilience and functional stability, while plantation systems, though productive, are relatively less efficient in sustaining decomposition-driven nutrient cycling

This study highlights the strong interplay between seasonal climatic variation, forest type, and ecosystem functioning in a subtropical hill forest of Nagaland, India. While seasonal changes in temperature, rainfall, and humidity governed the overall patterns of litter decomposition, soil properties, and microarthropod dynamics, the type of forest significantly modulated the magnitude of these processes. The natural forest, characterized by greater litter diversity, higher soil organic matter, richer nutrient pools, and more complex microarthropod assemblages, consistently exhibited higher decomposition rates and nutrient turnover compared to the plantation forest. These findings highlight the ecological importance of old-growth forests in sustaining functional stability, nutrient cycling, and biodiversity, whereas monoculture plantations, though useful for timber production, provide reduced ecosystem resilience and slower nutrient recovery.

Limitations

1. The study was limited to two forest types within a single district, restricting the broader generalization of results to other subtropical ecosystems with different vegetation or management regimes.
2. Litter decomposition was assessed primarily through mass loss and nutrient concentration, without detailed biochemical profiling (e.g., cellulose, hemicellulose, secondary metabolites) that could offer deeper insights into litter quality.

3. The focus was on soil microarthropods, while other decomposer groups (fungi, bacteria, macrofauna such as earthworms and termites) were not comprehensively assessed, potentially underestimating their role in nutrient cycling.
4. The two-year study period captured seasonal variability but may not fully represent interannual climatic fluctuations and long-term forest dynamics.

Future Prospects

1. Comparative studies across multiple forest types (e.g., secondary forests, mixed-species plantations, agroforestry systems) are needed to better understand how management practices influence decomposition and nutrient cycling.
2. Integrating advanced biochemical and molecular tools could help unravel microbial–faunal interactions and the mechanistic pathways driving decomposition under different environmental conditions.
3. Long-term monitoring should be undertaken to capture interannual variability and climate change impacts on litter dynamics and soil biodiversity.
4. From an applied perspective, incorporating native tree species into plantation systems may enhance biodiversity and restore ecological functions closer to those observed in natural forests.

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