



Impacts of Climate Change on Leaf Litter Chemistry and Decomposition in Forest Ecosystems

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ABSTRACT

Chemistry and decomposition of leaf litter are integral to the carbon cycle in forest ecosystems. As leaves detach from trees, they accumulate on the forest floor, forming organic matter that serves as a source of energy and nutrients for soil microorganisms. Leaf litter decomposition releases carbon dioxide into the atmosphere and returns nutrients to the soil, which plants absorb. Climate change is expected to affect leaf litter chemistry and decomposition in forests significantly. Elevated temperatures may accelerate leaf litter decomposition, increasing carbon dioxide emissions. However, higher temperatures could worsen soil water stress, reducing water availability for plant growth and potentially slowing decomposition. Changes in precipitation patterns, such as increased drought frequency, can influence leaf litter chemistry and decomposition. Drought conditions may reduce soil moisture, slow decomposition and alter nutrient balance within leaf litter. Increased rainfall can enhance decomposition by providing moisture to support decomposer organisms. The chemical composition of leaf litter influences its decomposition rate. Leaves from different tree species contain varying levels of nitrogen, phosphorus, and other nutrients, affecting decomposition patterns. The chemistry and decomposition of leaf litter are key components of the carbon cycle within forest ecosystems, influenced by environmental and biotic factors. As climate change advances, these processes will be affected in complex ways, highlighting the importance of understanding their mechanisms. This understanding is essential for sustainable forest management in a changing world.

Keywords: Leaf litter; temperature; rainfall; climate change; biotic factors; abiotic factors.

1. INTRODUCTION

The nutrient cycle between plants and soils is influenced by the amount of litter produced, its chemistry, and its decomposition (Yan et al., 2018). In terrestrial ecosystems, litter is a major pathway for the return of nutrients to the soil. About 70% of aboveground litter in forests consists of leaf tissue; the remaining material consists of stems, small twigs, and reproductive structures (Giweta, 2020). "Mass loss of litter" or "decay" is the sum of chemicals released and carbon dioxide released; these compounds include both nutrients and carbon compounds (Weil et al., 2010). Many processes contribute to litter decomposition, especially the heterotrophic consumption of organic litter composites (Bezkorovainaya et al., 2005). Although they contribute to litter decomposition, small insect activity, and rainwater leaching do not directly cause the release of carbon dioxide into the sky. Soil respiration, i.e. carbon dioxide emissions through the soil surface, can be increased by more than 20 % by the carbon dioxide released by microbial decomposition. Plants and microbes can take up nitrogen, phosphorus, and calcium, which are released from the plant litter during decomposition (Krishna and Mohan, 2017).

In a forest ecosystem, decomposition of litter is essential to maintaining the nutrient budget. The primary factor influencing the flora is the recycling of nutrients from plant litter (Vesterdal et al., 1999). The process of breaking down organic matter into carbon dioxide and nutrients through physical, biological, and chemical routes is known as litter decomposition (Aerts et al., 1997). Through the heterotrophic respiration of animals and soil microbes, it releases carbon dioxide back into the atmosphere (Chandrasekhara and Irmiler et al., 1997). Fast decomposition rates aid in meeting plant intake requirements, whereas slow decomposition rates cause organic matter and nutrient stocks to accumulate in the soil (S.R et al., 2005). Temperature, precipitation, and seasonal fluctuations are examples of climatic factors that can affect the presence of bacteria and other soil fauna that have a major impact on decomposition rate. The activity of soil communities and processes during decomposition are similarly impacted by the variety of litter (Koch et al., 2007). Except for earthworms, termites, and ants, the importance of many soil species to the ecosystem is little known (Lawton et al., 1994 and J.M. 1995) Decomposition of plant remnants or litter that fall to the ground including branches,

leaves, and reproductive structures, recycles around 90% of the net primary output of terrestrial ecosystems (Bergseng et al., 2012, Barlocher et al., 2007). One of the key processes in the biogeochemical cycles of forest ecosystems, as well as the preservation of soil fertility and the presence of microorganisms and invertebrates, is the ongoing return of organic matter and nutrients to the soil through the decomposition of litter (Jong et al., 2015).

The rate at which leaves decompose varies depending on the species and is influenced by the chemical composition, namely the stoichiometry and concentration of C, N, P, and lignin (Marin-Spiotta (2008) and J. M et al., 2012). Species with high leaf "quality," which is defined by a low C/N ratio, high N and P content, soft leaves, and little to no refractory substances like lignin and total phenols, see an increase in the rate of decomposition (Aryal et al., 2018). Many plants in the legume family, Fabaceae, have symbiotic interactions with bacteria that fix nitrogen, which may lead to the production of high-quality leaves (A.R et al., 2011 and Rozendaal et al., 2018). However, since harder or stronger leaves (with higher lignin, cellulose, and hemicellulose content) take longer to decompose, leaf toughness (LT) is a good indicator of Carbon investment in structural tissue for protection and negatively affects decomposition rates (Aerts et al., 2011).

A considerable proportion (550 Gt) of the total carbon stored in terrestrial ecosystems worldwide (861 Gt) is held in reserve by tropical and subtropical forests (Fang et al., 2011). However, due to changing decomposition rates, the projected increase in global average temperature by 2.6 to 4.8 °C by 2100 may drastically change the ability of these ecosystems to store carbon (Liang et al., 2019). By changing the activity of microbial extracellular enzymes and their community composition related to litter decomposition, climate change directly and indirectly influences decomposition (WHO, 2019). The mix of plant species is also affected by climate change, altering the quantity and quality of litter and the rate of its decomposition (Cacciatori et al., 2019). The litter bag approach was used to investigate how climate change affects the decomposition of litter. The decomposition rate of copper beech leaf litter is higher at warmer sites than at cooler sites in Italy (Schenk et al., 2015). Reduction in hard-to-reach fractions in Alaskan boreal forests as a result of increased microbial enzyme activity

was observed (Allison et al., 2017, Aggestam et al., 2020).

On the island of Hawaii, warming accelerated the process of nitrogen mineralization and shortened the time that litter remained on the forest floor (Selmants et al., 2014). A shortening of the half-life of the labile and recalcitrant fractions of litter with warming was also documented in Canada (Janzen et al., 2017). In an in situ warming experiment conducted in a temperate Sitka spruce forest in Ireland, warming has also been shown to increase the rate of heterotrophic respiration (Tobin et al., 2018). During a short microcosm warming experiment (+3°C), the rate of carbon dioxide emission from the soil was also higher (Liang et al., 2019). Soil respiration is also influenced by fluctuations in soil moisture and precipitation patterns. In a subtropical forest in China (Huui et al., 2017) found an increase in soil carbon dioxide emissions after rain. The decomposition rate decreased slightly as a result of the warming-induced decrease in litter moisture (Reibold et al., 2020).

To better understand ecosystem dynamics and predict future patterns of carbon cycling, it is essential to investigate how climate change affects the chemistry and decomposition of forest leaf litter. The decomposition of leaf litter has a major impact on carbon sequestration and nutrient cycling, which in turn affects soil fertility, microbial populations, and forest productivity. Changes in temperature, atmospheric carbon dioxide levels, and precipitation patterns caused by climate change are expected to lead to changes in the chemistry and decomposition rates of leaf litter. Studying these changes will help improve carbon cycle models and provide insight into how forests might adapt to climate variability. This knowledge will inform management and conservation strategies to reduce the negative impacts of climate change on forest ecosystems and their critical role in global carbon dynamics.

2. IMPORTANCE OF UNDERSTANDING LEAF LITTER CHEMISTRY AND DECOMPOSITION UNDER CHANGING CLIMATE

The impacts of litter are widely established in practical terms in many conventional agricultural operations. In low-technology agriculture, gardening, and modern horticulture, for instance, plant litters were used for mulching (Cardon et al., 2006, Berg and Laskowski, 2006) preventing soil freezing and erosion; shielding weed

infestation (Cardon et al., 2006) enhancing mine reclamation (Martins et al., 2013, Sanchez et al., 2018) preserving moisture and lowering evapotranspiration; and enhancing the function of the forest ecosystem (Mohan et al., 2007). Because nutrient cycling makes nutrients accessible for plant development, production in forest ecosystems is closely correlated with it (Table 1) (Mohan et al., 2007). Litter generation is typically used to evaluate primary production since it is the principal source of soil organic carbon (SOC) and plant nutrient cycling (Vitousek, P., 1982).

In the forest ecosystem, litter serves as an additional indicator of primary production alongside the height and diameter of the trees (Vitousek, P., 1982). Although the carbon cycle is determined by the decomposition of plant litter, as Fig. 1 shows, it also regulates the atmospheric carbon dioxide concentration, which affects the global climate (Krishna et al., 2007). Through the interplay of decomposers, litter quality, and abiotic variables (S.K et al.,2007) litter is broken down into smaller pieces and eventually mineralized into inorganic compounds. The following key processes affect litter over time, and these changes can be linked to them (Parrest et al.,2007).

- 1) Leaching is the process of moving soluble material to a lower soil layer so that decomposers can digest it further.

- 2) By physically breaking down big pieces of trash into smaller ones, fragmentation creates new surface areas for decomposers.
- 3) Chemical modification, or the change in the litter's chemical composition, happens when decomposers identify the molecules or utilize only a portion of them to produce decomposer biomass.

The decomposition of structural and soluble chemicals leads to changes in the chemical composition of the litter during the decomposition process (Malhi et al.,2009). The decomposition process is strongly influenced by soil fauna and microorganisms. Depending on the needs of the decomposer communities, the soluble nutrients can first be leached and then either mineralized or immobilized (Malhi et al.,2009). The amount of carbon in the litter decreases over time as the decomposers mainly use the organic carbon in the litter as an energy source. However, the speed and efficiency of the decomposers determine how much carbon is lost in the litter (Liu et al.,2012). Temperature, water availability, nutrient availability, and litter quality are the most important determinants of the development rate and efficiency of decomposers (Jorgensen et al., 2010).

Table 1. Impact of litter generation and breakdown on the physical and chemical environment, both directly and indirectly (Weirdt et al., 2012)

Effect	Mechanism
Diminish the soil's thermal amplitude	As litter builds up, it blocks light and shades seeds and seedlings, lowering the temperature of the soil (Mohan et al., 2007).
Lower the soil's evapotranspiration	Lower the maximum soil temperature; this will prevent the passage of water vapor (Malhi et al.,2009).
Reduce the amount of water available	A significant amount of rainwater may be retained in litter (Sanford et al., 1986).
Decrease the appearance of seedlings and the germination of seeds	Prevents seeds from penetrating soil and forms a barrier for the establishment of sprouts and seedlings (S.K et al.,2007).
Plant litter buildup in patches might change the makeup of the community.	A second species' performance may be impacted by the litter of a first species (S.K et al.,2007). Litter left by one species may change how a second and a third species interact (Budke et al., 2013).
Elevate the carbon dioxide efflux	More than 20% of the carbon dioxide outflow in the soil might come from microbial breakdown (Mohan et al.,2007).
Boost the soil's nutrient replenishment	A vital route for the return of nutrients to the soil is litterfall (Mohan et al.,2007).

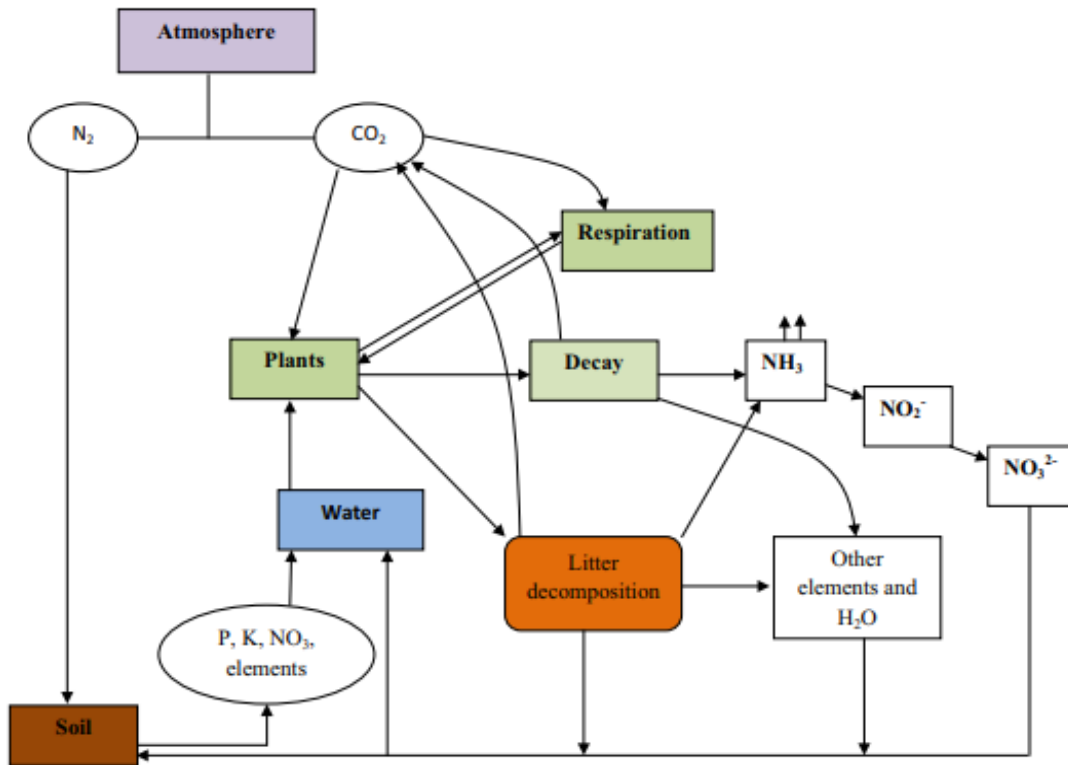


Fig. 1. Litter degradation's place in biogeochemical cycles (The different elements and compounds that build up in plants are released back into the environment when litter decomposes, allowing the chemicals to seep into the soil and disperse throughout the atmosphere. Thus, these materials are once more entering the biogeochemical cycle (Mohan et al.,2007)

Moreover, the production of carbon dioxide from dead organic matter during the decomposition of plant litter and the provision of nutrients for microorganisms and plants are essential ecosystem activities (Tripathi et al.,2004). The addition of litter to the various soil layers influences the soil's ability to absorb water and nutrients (Giller et al.,1997), hence improving the soil's ability to absorb water and nutrients. A high species variety within the forest ecosystem may lead to an increase in soil organic carbon and the C/N ratio (Sanford et al.,1986). Furthermore, diversified mixtures generate more litter—both in quantity and quality—than monocultures do. This might lead to an increase in carbon sock and aboveground productivity (Wiebe et al.,2014).

The dynamics of N and C during litter decomposition exhibit distinct patterns. Specifically, fresh litters often contain less N than what is required by the decomposers, which means that the decomposers will have to immobilize nitrogen from the surrounding environment (Wiebe et al.,2014). Eventually, the

N concentration will rise above the requirements of the decomposers, and the N: C concentration will be greater, indicating the beginning of the N mineralization process and substrate absorption (Pare et al., 2010). Consequently, N: C dictates both the N dynamics and the litter breakdown process.

3. FACTORS INFLUENCING LEAF LITTER CHEMISTRY AND DECOMPOSITION

The two simultaneous processes that make litter decomposition are (a) the humification and mineralization of lignin, cellulose, and other compounds through a series of microbial actions, and (b) the leaching of soluble compounds into the soil that gradually mineralize their carbon and nitrogen (Anderson 1988).These techniques rely on both biotic characteristics, such as the chemical makeup of soil organisms and litter, and abiotic variables, such as temperature precipitation patterns and moisture. Accordingly, the three main factors influencing litter decomposition are the physico-chemical

environment, litter quality, and the makeup of the decomposer community (Ruan et al.,2005). The factors responsible for litter degradation have been discussed below (Fig. 2).

3.1 Role of Temperature

Litter decomposition rates are largely influenced by temperature (Hobbie et al.,1996), and decomposition is more temperature-sensitive than primary production (Kirschbaum et al.,2000). The relationship between soil temperature and microbial activity is exponential. A few studies (Meentemeye et al.,2000) have suggested that the chemical makeup of the litter plays a part in its decomposition in addition to the climate. Soil macro- and microfauna can easily find a readily available substrate in newly fallen leaves. The breakdown process is also influenced by the quality of the litter, which often decreases as a result of the buildup of resistant chemicals and the loss of easily available carbon. The kind of leaf litter has an impact on soil microorganisms and the decomposition process, as demonstrated by Wang et al.,2010.

Decomposition rates are generally more sensitive to temperature than rates of net primary

production (Kirschbaum et al.,2000). Temperature is frequently the primary factor determining rates of litter decomposition (Hobbie et al.,1996). Accordingly, a warmer temperature may cause changes in the equilibrium between ecosystem C fixation and decomposition, which might result in a sharp rise in the amount of CO₂ that flows from soils to the atmosphere (Wilkinson et al., 2001).

3.2 Role of Soil Properties

The physical and chemical properties of the soil have a major influence on the decomposition of litter. The most important of these is texture, which increases surface area, porosity, permeability, and the dynamics of water and nutrients. The most important chemical characteristics are pH, cation exchange capacity, organic matter concentration, and nutrients. The most important soil characteristic affecting litter decomposition is organic matter, which influences many physico-chemical variables such as bulk density and pH (Blair et al.,1999). In addition, organic matter can increase the density of soil macroorganism populations, which is important for litter mixing and decomposition (Okoh et al.,2005).

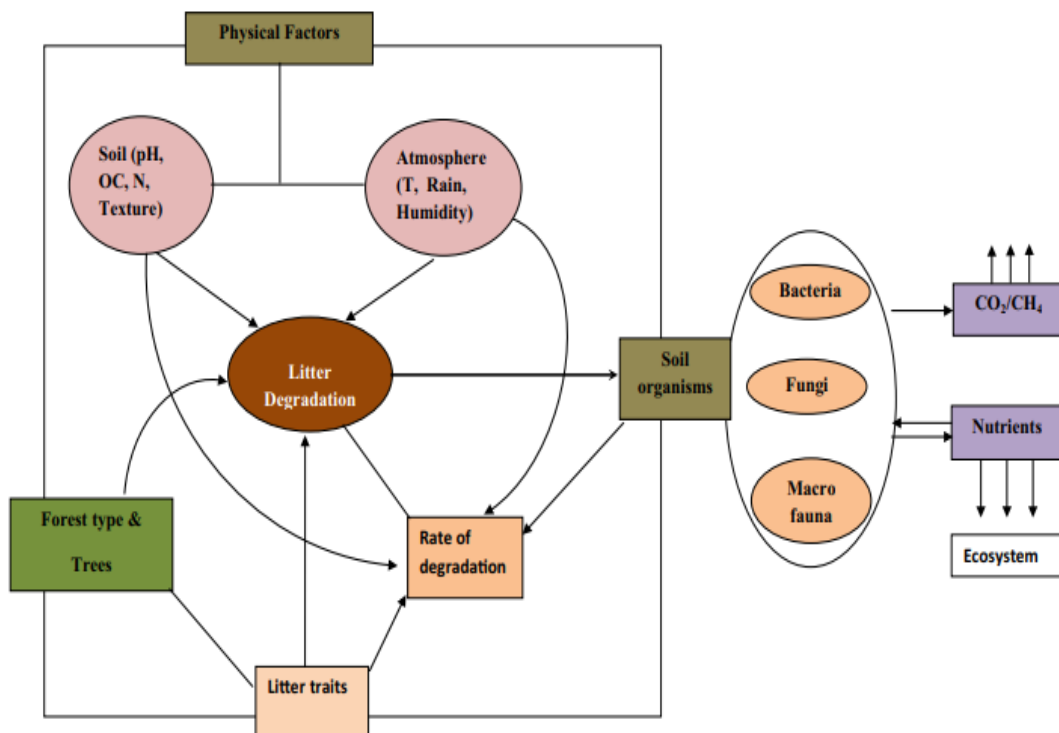


Fig. 2. (Mohan et al.,2007). Diagrammatic illustration of the variables influencing the decomposition of trash (a variety of physicochemical and biological elements impact litter degradation). The climate and kind of woods influence these parameters

Phosphorus is usually considered a limiting nutrient because it circulates poorly in large forests, while the nitrogen status of the soil is recognized as a fundamental regulatory component and has attracted the most attention among mineral nutrients. While the organic complexes in soil organic matter pools have much slower turnover rates and take many years or decades, calcium, nitrogen, and phosphorus in litter are mineralized rapidly (Yadav et al., 2007). However, when the entire decomposition process is considered, the effects of additional nitrogen on the rate of decomposition appear to be insignificant and may even be counterproductive.

Although magnesium and potassium are necessary minerals for higher plants, they scarcely restrict the activities of microorganisms and may be readily extracted from degrading litter. Because the nutrient cycles in rain forests vary depending on the kind of soil, the climate, and the topography of the area, temperature, and moisture content are also inevitable variables in the decomposition of litter (Welzl et al., 2011).

3.3 Litter and Tree Quality

The main source of organic matter in forest soil is vegetation, which partially penetrates the soil and is deposited as an organic layer or litter on the soil surface (Regina et al., 2001). Different types of organic compounds can be found in plant litter. Sugars, phenols, hydrocarbons, and glycerides are the four main groups of soluble organic material found in litter. The soluble carbohydrates, which are mostly mono- and oligosaccharides, are difficult to metabolize. The proportions of these substances vary depending on the type of plant (leaves, stems, roots, bark, etc.). The chemical composition of nitrogen, phosphorus, potassium, and important cell wall components such as lignin, cellulose, and hemicelluloses, which influence the decomposition of the litter and the release of nutrients, are used to assess the quality of the plant litter.

About 15–40% of the total amount of waste consists of lignin. The proportion of lignin in the waste can be between 4 % and 50 % in particularly severe cases. Unlike cellulose, lignin is an incredibly flexible molecule. Different plant species have different lignin structures. Conifers often have guaiacyl lignin, while deciduous tree species have different amounts of syringyl and guaiacyl lignin (Zimmermann et al., 2013). In addition to lignin, carbohydrates such as

cellulose and hemicelluloses are among the other predominant components of plant litter in terms of quantity. Cellulose (which makes up 10–50 % of the litter volume) consists of glucose units linked by β -1-4 bonds to form long molecular chains arranged in fibers. The proportion of hemicelluloses, which consist of sugars such as glucose, varies depending on the type of litter (Okoh et al., 2005). The ratio of hemicellulose to cellulose is between 0.7 and 1.2, whereby a higher ratio is often observed in a deciduous litter (e.g. beech) and a lower ratio in the coniferous litter (e.g. spruce). Species that decompose under the same ecological conditions differ greatly in their rate of litter decomposition (Bonner et al., 1997). Different litter properties, such as leaf toughness, nitrogen, lignin and polyphenol concentrations, C/N ratio, and lignin/nitrogen ratio, are primarily responsible for these changes in decomposition (Harguindeguy et al., 2000). The most important features controlling the rate of decomposition are the lignin and nitrogen content of the plant material (Cardon et al., 2004). As easily accessible carbon is lost during decomposition and refractory chemicals accumulate, the quality of the litter generally decreases. Since deciduous litter contains less lignin, more potassium and phosphorus and almost always fewer ether-soluble sections, conifer leaves decompose more slowly than deciduous leaves (Likens et al., 1973).

Acacia arabica litter decomposes more slowly than teak litter, and litter beneath forest canopy decomposes more quickly and is softer than leaves exposed to sunlight (Gadisch et al., 1997). In addition, leaf litter disappears considerably sooner than twigs and branches. Variations can also be seen in the pace at which the same plants' leaf litter decomposes at different times of year and in various locations (Tapwal et al., 2012). The primary element influencing litter decomposition on a wide geographic scale, according to studies (Vitousek et al., 2000), may be climatic fluctuations. Species having the highest ash and nitrogen levels, lowest C/N ratios, and lowest lignin contents decompose at a faster pace. It indicates that species with typical C/N ratios and average ash, nitrogen, and lignin concentrations decompose at a transitional pace. According to Gonzalez and Seastedt (2001), observed a gradual link between the ash concentration and the rate of degradation of hot-water soluble compounds (Seastedt et al., 2001). The types of litter influence the nutritional concentrations. The

nitrogen fixative genus *Alnus*, for example, contains leaf litter with high real concentrations of nitrogen (typically exceeding 3%); in contrast, pine needle litter has low nitrogen concentrations (sometimes around 0.4%). Thus, a distinguishing characteristic of the litter value is plant species (McClaugherty et al., 2003).

3.4 Microbes and Soil Fauna

At different phases of decomposition, the quantity and distribution of soil fauna and microbiological populations are known to impact the pace of litter breakdown (Dilly et al., 2004). The organic matter's microbial breakdown in forest soil has a big impact on the ecosystem's energy flow and soil carbon cycle. Such soil bacteria are thought to have a very wide diversity, although the majority of them are unknown (Prossor, 2002). Because of their high productivity and quick development, soil fungi have a significantly smaller species variety than bacteria (Bridge et al., 2001). One gram of soil contains hundreds to thousands of different bacterial species, although there are more than two or three million total species (Zabek et al., 2000). Fungi have a larger capacity to degrade organic matter than other microorganisms, with over 75% of them being the top decomposers among the soil microfauna. Additionally, the season will affect how active they are. Along with fungi, litter bacteria contribute significantly to the mineralization of organic matter and makeup about 25–30% of the total microbial biomass in soil (Munch et al., 2001). In nutrient-rich environments, the decomposition of leaves by bacteria and fungi is usually rapid. Stress conditions can have an opposite effect on the role that bacteria and fungi play in leaf decomposition.

Soil moisture can be a constraint for microbes as well. High rates of microbial activity are retained in soils with increasing soil moisture content as temperatures rise (Melillo et al., 1994). Consequently, with rising temperatures and precipitation, new litter decomposition rates increase. Decomposition may begin before litter falls due to the growth of bacteria, particularly fungus, on the litter; nevertheless, decomposers may not begin to proliferate until the litter touches the floor. The qualities of the litter, the characteristics of the soil, and changes in these factors over time determine how the microbial community occupying the litter is arranged (Nadelhoffer et al., 1999). According to earlier research (Table 1), which acknowledged the

involvement of various classes of bacteria and fungi in litter degradation, forest soil, and related microbial communities play a crucial role in the decomposition of litter in laboratory settings. Plant species have an impact on the quantity and quality of litter input, which in turn affects the breakdown of litter (Ineson et al., 1998).

In addition to bacteria and fungi, invertebrate micro- and macroorganisms make up the soil biota (Heath, 1996). Since they play an important role in the decomposition of organic matter, mineralization processes, nutrient cycling, and soil formation, microarthropods— living in the litter layers and the upper soil layer —are an important component of ecosystems. The main functions of soil fauna are to promote microbial activity and to support litter acclimatization. As soil bacteria can absorb the labile chemicals (such as sugars and amino acids) in the litter, it is more likely to decompose quickly (Hobbie, 1996). Exo-enzymes rapidly break down labile structural molecules such as cellulose into sugar subunits, which can then be easily absorbed by bacteria.

3.5 Biotic and Abiotic Factors Impacting the Amount of Litter Produced in Forest Environments

Many environmental and human variables influence the creation and accumulation of litter in forest ecosystems, and each of these elements has a major impact on its own or in combination with other ones (Tables 2 and 3).

3.6 Natural Disturbances and Anthropogenic Activities

It is evident that forests are complex systems with a variety of characteristics that interact with each other across larger geographic areas (Mohan et al., 2007). In general, stands with lower structural complexity support less stability and ecosystem functions, have lower species diversity, and are less stable than stands with higher structural complexity (Malhi et al., 2009 and Scheer et al., 2009). The composition and structural characteristics of forests can be severely affected by anthropogenic disturbances such as logging, fire, agriculture, livestock, and deforestation for fuel. In addition, both natural and human-induced disturbances can negatively affect the quantity and quality of annual litterfall, litter depth, stand basal area, amount of coarse woody debris, and understory density (Tripathi et al., 2004).

The percentage of litter fraction (such as reproductive parts, leaf litter, and twigs) varies according to the degree of disturbance at different sites (Zerihun et al.,2018). Compared to highly disturbed areas, less disturbed sites produce more litter fall annually. Less structural complexity results from the ongoing removal of logs for fuel and the cutting of snags (K. L., 2014). The understory will disappear and change when roads are opened for logging and timber production (Mishra et al.,2004).

Previous studies have also demonstrated that, in logged plots as opposed to undisturbed plots, snag density was three to five times lower (Triphati et al., 2004) and (K. L., 2014). The undisturbed plots had a higher basal area than the plots that had both fire and logging combined (Carmona et al., 2002). The structure of stands and their characteristics, including litter depth, basal area, and understory density, are significantly impacted by the presence of cattle, either alone or in conjunction with other disturbances (Carmona et al., 2002). Due to grazing and trampling the herbaceous layer, livestock also had a greater detrimental impact on understory structure and forest regeneration. Because plant biomass is found above ground, animal grazing would lower the amount of biomass needed for litter conversion (Gonzalez et al., 2005).

3.7 Seasonal and Climatic Variations

Seasonal variations can affect carbon exchange between terrestrial and atmospheric environments (Verbeeck et al.,2012). Seasonal variation in litter fall, i.e. the variation in litter fall among species within forests due to environmental factors such as light, temperature, and precipitation, has a significant impact on the dynamics of carbon and nutrient cycling in the ecosystem (Spies et al.,2002).

Seasonal precipitation and ambient temperature have a significant relationship with litter fall production (Zerihun et al.,2018). Precipitation affects litter production in two ways: First, it can cause senescent leaves to shed (Liu, L., 2012), and second, high precipitation at certain times of the year can shade non-senescent leaves (Scheer et al.,2009). Several authors have found that, in contrast to winter, the highest amount of litter fall was recorded in fall, summer, and spring (Martins et al.,2013 and Liu, L., 2012). Considering the strong positive correlation between season and climate variables, variations in both may have a significant impact on reproductive distribution. All these studies have shown that although the amount of waste produced in the tropical forest ecosystem varies according to the age and location of the different tree species, seasonal and local climatic conditions have a major influence.

Table 2. The major abiotic and biotic factors affecting in situ litter

S.No.	Environmental factors	Effects
1	Soil fertility	Plant litter will release nitrogen, phosphorous, and calcium during the breakdown process, making them available for absorption by plants and microbes. This might lead to an increase in the generation of in situ litter (Cadish et al.,1997).
2	Climate	The amount of rainfall and the length of the growing period influence the formation of in situ litter (Budke et al.,2013).
3	Evapotranspiration	Latitude and potential evapotranspiration are less relevant in explaining litter formation than actual evaporation (Budke et al.,2013).
4	Storms and winds	The rate at which plant organs turn into litter can be impacted by winds and storms (Cadish et al.,1997).
5	Time lag	In situ litter generation is determined by the interval of time between the creation of a plant organ and its deposition (Spies et al.,2002)
6	Herbivores	Herbivores can produce more or less litter, even though their intake often lowers the standing biomass (Vebeln et al., 2005).

Table 3. A list of the variables influencing the way that litter builds up

S. No.	Factors	Referred examples
1	Production of litter in situ	In situ litter generation is strongly influenced by the productivity of the plant community at a site (Gorham et al., 1964).
2	Litter accumulation from outside the system	Litter buildup is significantly impacted by both the addition of exogenous litter and the removal of native litter (Pabst et al., 2015).
3	Destroying litter by both physical and biological agents	The bulk of in situ litter accumulated may be decreased by physical and chemical deterioration, decomposition, and heterotrophic consumption. Ecosystems differ significantly in their rates of decomposition (Paustian et al., 1989).
4	Litter removal	Runoff, shrub geometry, wind, and water movement remove fragmented litter from open sites, which is the primary reason why litter disappears from any open sites (Pabst et al., 2015).
5	Temporal changes	Seasonal and successional changes in the environment can cause variations in the amount of accumulated trash (Paustian et al., 1987).

3.8 Species Diversity

In tropical forest soils, the fine litter, which includes roots, reproductive organs, and leaves, reaches 10-30 % of the net primary production that enters the surface litter layer, according to (Parkinson et al., 1987). It is therefore assumed that a total of 12 tons ha⁻¹ year⁻¹ of dead plant dry matter ends up in the soil. However, the annual litter input is influenced differently by each tree species that make up a particular forest ecosystem, which in turn has a significant impact on the total amount of litter produced and the litter pool (Veblen et al., 2005).

3.9 Basal Area, Density, and Age of Trees

The litter production of *Tectona grandis* increases with age (Austin et al., 2008). On the other hand, it was found that litter fall alone is linearly related to age, as litter production may decrease with canopy closure (Gorham et al., 1964). Although the age of the tree has no direct influence on the amount of litter fall produced, several authors (Tripathi et al., 2004) have shown that age, density, and basal area in combination can have a significant influence on litter output.

3.10 Vegetable Structural Pattern

There is a positive correlation between the basal area of tree layers and litter production when certain species are strongly represented or dominant due to selection effects. A larger basal area and volume in dominant species can lead to significant leaf loss throughout the year and improve the uptake of nutrients by the soil

(Gomez et al., 2014). Litter production is directly influenced by species variation in dominance, volume, and basal area. For example, for some tree species, dominance, volume, and basal area have positive relationships in the higher strata but negative relationships in the lower strata (Gomez et al., 2014).

4. VARIOUS METHODS FOR STUDYING LEAF LITTER CHEMISTRY AND DECOMPOSITION

The fall of plant litter serves as the main channel for the replenishment of soil nutrients in terrestrial systems. In forests, leaf tissue can account for 70% or more of aboveground litterfall; stems, small branches, and reproductive structures make up the remaining litterfall (G.P et al., 1999). Several processes, such as heterotrophic utilization of organic compounds in litter, leaching during rain events, and decomposition by tiny insects, all contribute to litter decomposition and prevent the direct release of CO₂ into the atmosphere. Based on sources referenced, three hypotheses are proposed to explain how initial litter quality affects litter decomposition and the release of nitrogen from decomposing litter. The first hypothesis states that initial litter quality is positively correlated with litter decomposition and nitrogen release. The C: N ratio is possibly the most accurate indicator of mass loss and N release in the early stages of decomposition, with lignin content becoming more important as litter decomposition progresses. According to the decomposition filter theory, variations in the initial quality of the litter (such as the ratio of lignin to N and lignin to cellulose) affect the release and

decomposition rates of the litter in its early stages. The initial quality of the litter has less and less effect on the decomposition rates in the later stages as the quality of the litter substrate decreases during decomposition. At this point, the external supply of labile C and nutrients, soil conditions, and temperature regulate the rate of litter decomposition. According to the third hypothesis, N-based estimations of the initial litter quality are inversely correlated with rates of litter decomposition and N release. Later in the breakdown process, high N content may slow down the pace at which litter breaks down, especially if there is also a high concentration of lignin. Notwithstanding the underlying processes, routine measurements of litterfall and litter decomposition using accepted methods will supply vital data on the cycling of carbon and nutrients in forests.

4.1 Mass Balance Techniques

Litter decomposition in various habitats is assessed using mass balance techniques (W.H. et al., 1997). This approach assumes that the detrital litter amount decays at a fixed proportion, k :

$$\text{Litter fall} = k (\text{detrital litter mass})$$

Values for k are greater than 1.0 in forests. k values are smaller than 1 in environment with limited surface litter deposition and slow rates of degradation. Litterbags are randomly placed across the research area and used to monitor the amount of litter falling (Hirata et al., 2002).

Model projections can be validated or trash degradation assessed using the mass balance approach (Hedin et al., 2000). If the forest floor is quickly deteriorating, the method would overestimate the rates of deterioration. Unlike litterbag tests, which can effectively explain the function of variables like temperature and moisture, this strategy relies on natural litter fall.

4.2 Litterbag Technique

Decomposition near the soil's surface is widely studied using the litterbag approach. To estimate the residual amount, fresh leaf litter is added to litter bags, which are then buried in the soil's litter layer and periodically collected. The typical goal of mesh size selection is to minimize excessive particle loss while increasing the number of organisms that can enter the litter. The microbial composition has been manipulated by using

litterbags with varying mesh sizes (Hoglund et al., 1962). In addition to preventing particle loss to mineral soil, very fine mesh sizes will also keep some organisms in place. For areas with high light levels, fiberglass mesh has been recommended since UV radiation deteriorates nylon and other materials (Nadelhoffer et al., 1999). However, 1-2 mm mesh is best for litterbag research (Robertson et al., 1999); macrofauna cannot enter if the mesh size is less than 2 mm.

Litterbag studies continue to heavily rely on the size and contents of the bags. A 20 x 20 cm litterbags are frequently used in various plant communities or in areas with huge leaves where a larger litterbag would be more appropriate (Robertson et al., 1999).

4.3 Tethered Leaves Technique

The litterbag approach and the tethered leaf method are comparable. The particular leaves are bundled firmly and placed in packets like litter bags. A single leaf or a collection of leaves is fastened together using a monofilament fishing line or nylon thread. For stability, the line is fastened to the petiole of the leaf; normally, it is fastened to a tag for identification and a coordination point to enable collecting. In terrestrial investigations, a "wheel spoke" approach—named is commonly employed (Turner et al., 1994). In this procedure, a set of particular senescent leaves are air-dried, once again with their petioles connected to a single line. Both ends are still fastened to a labeled washer and a recognizing tag. In this way, many sets of threads are linked to each washer.

Tethered leaf studies are still highly useful for understanding the early stages of degradation, thus the duration of the research is not the same as that of litterbag approaches. Compared to the litterbag method, this approach will overestimate the rates of decay when the leaves start to break. The research found that invertebrates that feed on litter may come into close contact with the material in litterbags that have mesh diameters as tiny as 1.5 mm (Turner et al., 2000). However, macroinvertebrates such as crabs and snails can consume leaves thanks to the tethered leaf approach; otherwise, their interaction would be limited to mesh bags.

4.4 Cohort Layered Screen Technique

The litter sandwich method, also known as the cohort layered window screen method, is a fourth

Table 4. Comparing several methods for studying the breakdown of litter (Scott et al., 2008)

Methods used for evaluating litter decomposition	Output	Drawbacks
Mass balance techniques	Evaluate litter decay, check on model forecasts	Litterbag investigations indicate that other factors like moisture and temperature cannot be well explained by this technique.
Litterbag technique	Decay at the soil surface	Large mesh sizes result in the loss of minerals to the soil and allow macrofauna to enter the bag.
Tethered leaves techniques	Finding out about the first stage of deterioration	It is not employed for the microbial decomposition of trash because it permits macrofauna to enter, and mesh sacks are used to restrict their interaction.
Cohort layered screen technique	long-term (greater than three years) study on litter degradation	Aluminum should not be used in place of fiberglass screens if any chemical or necessary qualities need to be assessed.

technique for evaluating high levels of leaf litter degradation. This method involves using layers of mesh screen to divide successive litter sheets on the forest floor, where the leaf litter decomposes naturally on top of the preceding litter layer.

For long-term degradation investigations, which typically last three or more years, the cohort layered screen method is used (Binkley et al., 2002). There's a fresh screen window above the forest floor after the annual fall of trash. A 1 x 1 m glass or aluminum window screen with a 2-3 mm mesh size is typically utilized. The size of the stand being tested will dictate the screen's dimensions, and the specific ecosystem being studied will influence the mesh size. If any chemical or vital characteristics are also going to be examined, a fiberglass screen is preferred over an aluminum one.

Every year after the first litter falls during the research period, a new screen is placed just over the old one. The subsamples are collected, weighed, and dried in an oven. The litterbag methodology is a more suitable method, according to a comparison of several methodologies employed in the research of litter degradation (Table 3).

5. IMPLICATIONS FOR FOREST MANAGEMENT AND POLICY

The primary goal of forest management has shifted significantly in recent decades, with wood

extraction no longer being the sole or primary goal. Actually, a wide range of ecosystem services (ES) are taken into consideration in the current trend that has emerged, which is clearly focused on the multifunctionality of forests. But despite initiatives to support provisioning and regulate ES at the same time, forest managers and policy officials still find this difficult (Nilsson et al., 2000). Because of this, forest management practice has occasionally turned to creating distinct zones where the goal is to achieve one or more of these ES and/or measuring the trade-offs associated with them (Sallnas et al., 2006). Forest managers have suggested that in order to conserve biodiversity, they should either segregate the forest's less productive areas or protect areas with high conservation value (Balterio et al., 2023). Additionally, growing interest in biodiversity protection has prompted the introduction of a number of measures, such as legally protected areas (PAs) (Frank et al., 2003) or the adoption of non-intervention areas, where forest management practices have been completely or partially abandoned. The designation of PAs is now a widely accepted tool for the conservation of natural resources.

Currently, segregated and integrated approaches to forest management are the two methods intended to incorporate biodiversity conservation in managed forests (Balmford et al., 2021). According to land-use zoning, segregated management seeks to maximize the availability of various ES independently in stratified forest regions (Binkley et al., 1997). This allows for the

complete protection of certain areas of the forest and varying degrees of management of other areas. As an illustration of this approach, consider the Triadforest management system, which is predicated on the division of three zones based on the intended goal: a conservation area to be managed independently, an extensive harvesting area, and an intensive harvesting area (Balteiro et al., 2023). On the other hand, various forest ES are intended to be provided within the same geographical context by integrated or integrative management (Sotirov et al., 2020). The official application of this kind of strategy in forest policy and the predicted level of attainment for various competing objectives (Sotirov et al., 2020) have, however, generated discussion. Additionally, there is ongoing debate about the proper thresholds for biodiversity preservation and the resulting economic impacts (Framstad et al., 2012).

To achieve multifunctionality in managed forests at various levels and scales, appropriate silvicultural options must be identified, regardless of the method ultimately employed (Balteiro et al., 2023). In this regard, it is evident that silviculture needs to change to satisfy modern societal expectations and adjust to the effects of a changing climate (Balteiro et al., 2023). The usual methods for achieving multifunctionality are employing natural disturbance-based systems (Framstad et al., 2012), prohibiting cuttings, or changing harvesting systems (which results in changes in silvicultural practices (Franklin et al., 2006). Reducing cutting areas (Balteiro et al., 2023), leaving trees or forest areas perpetually uncut lengthening the rotation period (Monkkonen et al., 2014), encouraging uneven-aged silviculture (Ezquerro et al., 2023) are a few of these changes.

New alternatives to silviculture have resulted from these changes (Ezquerro et al., 2023). In addition, different forest policies that embody the idea of close-to-nature forestry are being developed in Europe, despite regional variations in the situation (Parviainen et al., 2003). Silvicultural alternatives like Continuous Cover Forestry (Ezquerro et al., 2023), Green Tree Retention (Franklin et al., 2006), Emulating Natural Disturbance (Ezquerro et al., 2023), or Ecological Forestry are the results of these changes aimed at integrated management (Makela et al., 2012) all of these options aim to increase structural complexity, biodiversity, and the variety of habitats available to sensitive species in managed forests.

6. CONCLUSION

Ecosystems depend heavily on the breakdown of litter because it is a key mechanism for recycling nutrients, particularly carbon and nitrogen, as well as other components. Different types of ecosystems have different rates of mineral intake and plant material breakdown that are in balance. Little is known about the pace at which litter decomposes and the roles that different components play in distinct ecosystems. Litter decomposition is a very complicated process that incorporates several physical, chemical, and biological elements. The pace of trash degradation is also highly variable, making it challenging to comprehend. Numerous distinct elements contribute to its deterioration. Studying litter degradation in light of the growing human influence on biogeochemical cycles is crucial. This review focuses on several variables that influence the different polymers in leaf litter and their breakdown patterns. Therefore, future studies must be focused on the following topics: (a) developing a technique for estimating the rate of litter degradation; (b) the relationship between litter degradation and climate change; and (c) the routes by which components are transported during litter degradation.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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