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# Unlocking the Potential of Microbial Biomass for Carbon and Nitrogen Transformations in Forest and Desert Soils: Review

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## ABSTRACT

Microbial biomass plays a prominent role in nutrient transformation and conserving forest and desert soils. The main aim of the present study is to summarize the effects of the dynamics of these transformations on soil quality. Microbial biomass and its activities are remarkably influenced by several variables: temperature, soil moisture, heavy metals, microbial community composition, predation and grazing, and soil texture. Microorganisms play a significant role in the elemental and energy movements, and they are frequently regarded as the catalyst or driving force behind the breakdown processes. Microbial biomass to organic carbon ratio specifically reflects the role of microorganisms in carbon availability. Soil microbial biomass carbon has been reported to be significantly greater in the top 0–30 cm depths compared to the lower depths. Several variables influencing the dynamics of soil microbial biomass are discussed in this review.

**Keywords:** Desert soil; Forest soil; Fumigation extraction; Microbial biomass carbon; Microbial biomass nitrogen.

## 1. INTRODUCTION

Microbial biomass (MB) comprises various microorganisms such as bacteria, actinomycetes, fungi, algae, and protozoa. These organisms constitute a labile nutrient pool within the soil (Das *et al.* 2023). Specifically, MB refers to the living portion of organic matter in soil. Its size is typically less than 5-10 µm³ (Harris and Steer, 2003). One critical component of soil ecosystems is Microbial Biomass Carbon (MBC), which includes archaea, bacteria, and eukaryotes (excluding roots and smaller animals) (Wu *et al.* 2021). Soil microbial biomass plays a pivotal role in transforming organic matter into simple inorganic compounds, making them available for plant uptake. Additionally, microbial activities involved in nutrient mineralization, particularly carbon, nitrogen, and phosphorus, are essential for biogeochemical cycling (Babur and Dindaroglu, 2020; Sunish and Thazeem, 2023).

Microbial activities are essential for the biogeochemical cycling of important nutrients such as carbon, nitrogen, phosphorus, and other micronutrients. (Jacoby *et al.* 2017). Beyond nutrient cycling, soil microorganisms also contribute significantly to organic matter degradation, nutrient conversion, and supply. (Zhang and Chu, 2011). The decomposition of organic matter is considered a beneficial relationship between the invertebrate fauna and the microflora, following leaching, comminution, humification, and mineralization processes. In addition to controlling nutrient availability, release, and circulation, the process also affects productivity levels and the balance of organic matter in the ecosystem (Verhoef and Brussaard, 1990). The decomposer community, which includes bacteria, fungi, actinomycetes, protozoa, nematodes, earthworms, enchytraeids, collembola, mites, and mollusks, is responsible for the transformation and decomposition of organic waste in terrestrial environments. Microorganisms like fungi, bacteria, and actinomycetes are among the decomposers that are capable of degrading complex materials such as cellulose, hemicellulose, and lignin, since they have extracellular enzymes (Anderson *et al.* 1981).

Siu and Skujins have highlighted the crucial role of various microorganisms in breaking down organic materials in soil through the production of proteolytic or cellulolytic enzymes (Siu and Ralph, 1951; Skujins and McLaren, 1967). Despite constituting only 1 to 4% of total soil organic matter, microbial biomass serves as a labile reservoir for essential plant nutrients, including nitrogen, phosphorus, and sulfur. In arable temperate soils, it can hold up to 100 kg N $ha^{-1}$ (kilograms of nitrogen per hectare), while grassland or forest soils may contain even higher amounts. The efficient cycling of nutrients within organic pools spanning plants, microorganisms, and organic waste is critical for both natural and agricultural ecosystem fertility. During biomass turnover, nutrients become accessible, turning the biomass into both a nutrient source and a sink (Singh *et al.* 1989). Soil microbial biomass, a key biological component, influences decomposition, nutrient cycling, and aggregation. Soil Microbial Biomass Carbon (SMBC), routinely measured, represents only a fraction of the total soil organic carbon content. Measurement of soil microbial biomass carbon provides a more sensitive indicator of change than soil chemistry alone, bridging the monitoring gap between soil chemistry and vegetation cover assessments. The microbial C to organic C ratio reflects microorganisms' role in soil carbon availability (Sanjoy *et al.* 2011). Consequently, soil microbial biomass serves as a crucial index for evaluating the impact of various development and management practices on soil quality and ecosystem function (Srivastava and Singh, 1991). The permaculture approach involves mimicking natural ecosystem processes by incorporating organic amendments, minimizing soil disturbance through no-dig raised beds, and promoting crop diversity and rotation. These practices enhance microbial activity and synergize with plant growth, leading to a dense network of hyphae within the soil. As a result, permaculture-managed soils exhibit much higher levels of carbon, nutrients, and organic matter compared to conventionally managed soils (Williamson *et al.* 2024).

## 2. MICROBIAL BIOMASS CARBON AND NITROGEN (MB-C AND MB-N) IN FOREST SOIL

Forest soils harbor the most abundant microbial populations, primarily bacteria, which represent one of the most diverse communities on Earth (Nacke *et al.* 2012; Hardoim *et al.* 2015), These soils exhibit distinct vertical layers characterized by gradients in organic matter content and susceptibility to erosion (Cochran *et al.* 1989; Diaz-Ravina *et al.* 1995). Forests act as major carbon sinks on Earth (Yavitt' *et al.* 1993) They contain more organic matter than other ecosystems, with forest soils storing a significant proportion (up to 50%) of the total soil organic carbon (SOC) globally (ŠANTRůčková, 1992; Scholle *et al.* 1992; Pietikäinen and Fritze, 1993), In forest ecosystems, soil carbon has an extended residence time, indicating their long-term role in carbon sequestration (Sarig and Steinberger, 1994). This layering significantly impacts both the quantity and quality of organic matter, with concentrations generally increasing with depth (Gallardo and Schlesinger, 1994; Holmes and Zak 1994; Wardle 1998). As a consequence, the elevation in organic matter content results in a proportional augmentation of microbial abundance and metabolic activity. These microorganisms exhibit an enhanced capability to decompose organic matter by synthesizing extracellular enzymes (Luizao *et al.* 1992; Hossain *et al.* 1995; Maxwell and Coleman, 1995; Maithani *et al.* 1996). Studies have shown that bacterial biomass in forest soil can be up to 8-fold higher in deeper layers compared to surface layers (Raghubanshi, 1991; ŠANTRůčková, 1992). Similarly, enzyme activity can exhibit a 5- to 20-fold increase with depth (Srivastava and Singh, 1991; Baldrian *et al.* 2010).

**Table 1. Seasonal dynamics of MB-C and MB-N in forest and arid soils**

| Location | Coefficient of variation (%) | | Reference |
|---|---|---|---|
| | Biomass C | Biomass N | |
| Orissa, India | 4 | | (Basu and Behera, 1993) |
| Solling, Germany | 10.9 | 11.9 | (Bauhus and Bartsch, 1995) |
| Central Alaska | 53.9 | | (Cochran *et al.* 1989) |
| Galicia, Spain | 25.5 | 25.6 | (Diaz-Ravina *et al.* 1995) |
| North Carolina, U.S.A. | | 12 | (Gallardo and Schlesinger, 1994) |
| Michigan, U.S.A. | 15.8 | 9.2 | (Holmes and Zak, 1994) |
| Near Canberra, Australia | | 15.2 | (Hossain *et al.* 1995) |
| Amazonia, Brazil | 28.4 | | (Luizao *et al.* 1992) |
| Meghalaya, India | 30 | 34.7 | (Maithani *et al.* 1996) |
| Sthn. Appalachians, U.S.A. | 19.6 | 32.7 | (Maxwell and Coleman, 1995) |
| Uttar Pradesh, India | 27.4 | 26.2 | (Raghubanshi, 1991) |
| Chalice, Czech Rep. | 37 | | (ŠANTRůčková, 1992) |
| Uttar Pradesh, India | 28.1 | 28.1 | (Srivastava and Singh, 1989) |
| Augsburg, Germany | | 20.9 | (Von, *et al.* 1992) |
| Panama Canal zone | | 37.9 | (Yavitt *et al.* 1993) |
| Evo, Finland | 11.5 | 10 | (Pietikäinen and Fritze, 1993) |
| Chalice, Czech Rep. | 43.5 | | (ŠANTRůčková, 1992) |
| Solling, Germany | 38.9 | | (Scholle *et al.* 1992) |
| Augsburg, Germany | | 16.1 | (Von *et al.* 1992) |
| Israel | 49.8 | | (Sarig and Steinberger, 1994) |

*Adapted from Wardle 1998, Soil Biology and Biochemistry, Volume 30, Issue 13, 1998, Pages 1627–1637*

Table 1 suggests that the MB-C and MB-N coefficient ratios of semi-arid Indian soil are the best (Wardle, 1998), including good microbial biomass and its activity. Temperate soils also show the best biomass coefficients with significant rates. The other tropical soil from Meghalaya, India is also in the range of good coefficient ratios for both carbon and nitrogen. Soils of Germany and Finland also have good ratios for microbial biomass while other temperate soils from arid regions and cold climates, which showed a non-significant ratio of MB-C and MB-N coefficients. Both tropical and temperate soils show good MB-C and MB-N coefficient variation. This also proves the correlation between soil physicochemical properties and environmental conditions, which direct the increment of microbial biomass and the transformation of elements in the soil.

Forest soils exert a substantial influence on various critical factors within the ecosystem, including the composition of the forest sand, ground cover, tree growth rates, and the vigor of natural reproduction. These factors are of significant importance in silviculture (Bhatnagar 1965; Gautam and Mandal, 2013). Despite making up just (1-4%) of the total soil organic matter, microbial biomass serves as a significant labile store for vital plant nutrients. Arable temperate soils can readily hold total nitrogen of 100 kg N ha$^{-1}$, and this amount can increase by two to three times in grassland or forest soils. The consensus is that the fertility of both natural and agricultural ecosystems is significantly influenced by the efficiency of nutrient cycling within the organic pools of plants, microorganisms, and organic waste. Therefore, during the biomass turnover process, when nutrients become available, the biomass acts as both a reservoir and a provider of nutrients (Singh *et al.* 1989). Wardle's research has shown that several studies have drawn comparisons between the microbial biomass found in conventionally tilled and non-tilled plots within agricultural systems. The majority of these studies have discovered that the microbial biomass is most abundant at the surface of plots with minimal tillage (where crops are directly drilled) due to the presence of plant residues. In contrast, in conventionally tilled plots, the microbial biomass is more evenly distributed throughout the profile (Lynch and Panting, 1980, 1982; Carter and Rennie, 1982, 1984; Carter, 1986, 1991; Doran, 1987; Granatstein *et al.* 1987; Haynes and Knight, 1989; Saffigna *et al.* 1989; Haines and Uren, 1990; Dalal *et al.* 1991; Hassink *et al.*1991, and Cochran *et al.*, 1989). This observation coincides with higher levels of organic carbon and nitrogen found at the surface of non-tilled systems (Fleige and Baumer, 1974; Doran, 1980). Moreover, a larger proportion of organic carbon is immobilized in the microbial biomass of non-tilled systems (Saffigna *et al.* 1989; Carter, 1991), suggesting that microbial biomass could serve as an effective 'early indicator' of changes in organic matter (Wardle, 1992).

Nitrogen is often the nutrient in the shortest supply, and it is introduced into the ecosystem via fixation. Bacteria, which are thought to contribute over 95% of the nitrogen in unmanaged environments, primarily carry out this process (Reed *et al.* 2011; Berthrong *et al.* 2014). Alphaproteobacteria (Azospirillum, Bradyrhizobium, Gluconacetobacter, and Hyphomicrobium) and Deltaproteobacteria (Geobacter spp.) have been reported in different temperate forest soils. N-fixing bacteria are ubiquitous in nature, occurring as symbiotic and free-living taxa (Vaninsberghe *et al.* 2015).

**Table 2. Microbial biomass C ratio in forest soil**

| Site Description | Types of Soil | MBC (mg/kg of soil) | References |
|---|---|---|---|
| Restored mine spoil (India) | Under plantation:<br>*A. lebbeck*<br>*A. procera*<br>*T. grandis* | 301.5<br>241.7<br>179.1 | (Singh *et al.* 2004) |
| Reclaimed post-mining sites near Sokolov (Czech Republic) | Alder Sites:<br>0-5 cm layer<br>5-10 cm layer<br>Oak plus geogenic carbon Addition site:<br>0-5 cm layer<br>5-10 cm layer<br>Pine minus geogenic carbon site:<br>0-5 cm layer<br>5-10 cm layer | 200-600<br>50-300<br>250-1100<br>150.0<br>50-250<br>150-350 | (Šourková *et al.* 2005) |

| | | | |
|---|---|---|---|
| Agriculture systems under polluted field trial (Australia) | Across field trials soils:<br><br>Uncontaminated soils: | 216 to 557<br><br>162 to 659 | (Bastida *et al.* 2007) |
| Reforestation practice site (South-eastern Spain) | Natural soils without any amendments:<br><br>Spring, Summer and Winter<br>Natural soil with organic matter amendments:<br>Spring, Summer, and Winter<br>Stripe management soil:<br><br>Spring, Summer and Winter<br>Terraces soils with organic residues amendment:<br>Spring, Summer and Winter | 560.4 ± 62.9, 161.3 ± 13.8 and 145.1 ± 6.9<br><br>577.4 ± 41.8, 166.0 ± 2.8 and 251.5 ± 14.6<br>674.2 ± 3.21, 186.4 ± 8.03, 311.6 ± 7.7<br><br>729.5 ± 12.6, 479.3 ± 14.6 and 535.1 ± 3.7 | (Broos *et al.* 2007a) |
| Agricultural field, (Central Zimbabwe) | Non-tillage soils:<br>Conventional tillage soils: | 534-802<br>452-667 | (Nyamadzawo *et al.* 2009) |
| Coal mining ecosystem (India) | Under plantation:<br>*M. oleifera*<br>*A. marmelos*<br>*T. garndis* | 600.0<br>590.0<br>50.7 | (Broos *et al.* 2007b) |
| Greenhouse soil (China) | Under furrow treatments:<br>Subsurface treatments<br>Drip irrigation treatments | 126-356<br>305-122 | (Sinha *et al.* 2009) |
| Udaipur, Rajasthan, Western (India) | Butea plantation:<br>Grassland:<br>Agricultural land: | 184.5-1387.7<br>119.1-435.7<br>89.6-335.7 | (Vidyanagar, 2010) |
| Revegetated quarries (Southern China) | 0-5 cm soils<br>5-10 cm soils | 102-378<br>49-196 | (Xu *et al.* 2013) |
| Global distribution biome | Boreal Forest:<br>Temperate coniferous forest:<br>Temperate broadleaf forest:<br>Tropical /subtropical forest:<br>Mixed forest: | 59.2-126.2<br>35.4-50.5<br>38.4-52.0<br>30.7-41.5<br>40.6-48.9 | (Xu *et al.* 2013) |
| Central Himalaya, (India) | Natural forest:<br>Hilltop<br>Hill slop<br>Hill base | 661-697<br>718-737<br>730-751 | (Vidyanagar, 2010) |

Table 2 shows the microbial biomass carbon in different soil types and at different soil depths (0–5 cm and 5–10 cm) with seasonal variations (summer, winter, and spring).

## 3. MB-C AND MB-N IN DESERT SOILS

A significant part of the earth's surface is made up of arid, semi-arid, and hyper-arid areas. The existence of life in these regions is significantly impacted by severe environmental conditions such as water scarcity, intense solar radiation, temperature variations, as well as soil salinity, and lack of nutrients. These factors pose serious threats to the growth and survival of plants. In recent times, there has been a growing fascination with plants that thrive in these harsh conditions and the advantageous microbes naturally associated with them. The rhizosphere, rhizosheath, endosphere, and phyllosphere of desert plants provide an ideal environment for discovering new microbes. These microbes are well-suited to extreme conditions and represent an untapped source of bio-fertilizers and bio-control agents that can combat a variety of abiotic and biotic stresses threatening various agricultural ecosystems. The characteristics of these microbes can be harnessed to enhance soil fertility, boost plant resilience to diverse environmental stresses, and improve crop yield. They also have the potential to promote human health and provide sufficient food for an expanding human population in an eco-friendly way. Numerous endeavors have been initiated to investigate the potential use of these beneficial microbes. In this overview, the attempts to uncover the bacterial diversity linked with desert plants in arid, semi-arid, and hyper-arid regions, emphasizing the most recent findings and applications of bacteria promoting plant growth from the most extensively researched deserts globally are discussed (Alsharif *et al.* 2020).

In arid lands, soil salinity and alkalinity contribute to the poor physicochemical properties and low fertility of many soils (Dang *et al.* 2022). Moreover, the unforgiving climatic conditions in these lands heighten soil vulnerability to the impacts of climate change and unsustainable human activities. Consequently, prioritizing sustainable agricultural practices becomes crucial for enhancing soil quality and overall health. A study discovered that amending a calcareous saline soil not only improved its quality and health but also promoted plant growth (Al-Mayahi *et al.* 2024). In deserts experiencing urbanization, soil respiration is influenced by anthropogenic nitrogen inputs from urban activities. Despite this influence, plant islands play a central role in orchestrating microbial processes. Investigating the impact of atmospheric deposition on soil microbes is challenging due to varying temporal and spatial scales. Microbial activity follows precipitation events like a brief pulse, while deposition patterns are influenced by weekly fossil fuel consumption and seasonal climate variations. Microbes concentrate beneath plant islands ($m^2$), while deposition affects entire airsheds ($km^2$). Understanding soil responses to increased nitrogen loading is crucial, given its correlation with human population growth in arid regions (McCrackin *et al.* 2008). All climate models predict that major hot desert regions worldwide will become hotter and drier. This will directly impact soil water availability due to reduced rainfall inputs and a lower aridity index (P/PET ratio). The projected consequences include increased aridification, expanding existing dryland and desert areas, and transitioning regions from arid to hyper-arid status. Such changes can significantly affect both macrobiology and microbiology, leading to species loss, reduced primary production, soil organic carbon decline, and decreased atmospheric nitrogen fixation. Phototrophic and diazotrophic processes, critical for soil nutrient cycling, are particularly sensitive to cellular water activity (Cowan *et al.* 2023).

## 4. MEASUREMENT OF MB-C & MB-N IN SOILS

### 4.1 Measurement of MB-C through Fumigation Extraction (FE) Method

This method, first used by (Vance *et al.* 1987), involves treating both fumigated and non-fumigated soils with $CHCl_3$ fumes under moist conditions for an incubation period of 18-20 hours. Following 24 hours of fumigation, the soils are then extracted with a 0.5 M $K_2SO_4$ solution at a soil-to-extractant ratio of 1:2.5 for 30 minutes under shaking co-addition. The non-fumigated soils are extracted with 0.5 M $K_2SO_4$ simultaneously with the initiation of the fumigation of the other set of soils. Biomass C is subsequently estimated from the increase in $K_2SO_4$-extractable organic C following $CHCl_3$-fumigation (Ec), where Ec equals the organic C extracted by $K_2SO_4$ from the fumigated soil minus the C extracted by $K_2SO_4$ from the non-fumigated soil. The $K_2SO_4$-extractable organic C is measured by two different methods: dichromate digestion (Fig.1) and an automated UV-persulfate oxidation method (Joergensen *et al.* 2011) During $CHCl_3$ fumigation, sulfur is also released from the biomass and its measurement after extraction can be used to estimate biomass. The FE method offers several advantages over the FI method. Biomass measurements can be made across the entire pH range and in soils containing actively decomposing substrates, in the field, or in freshly sampled soils, in all the conditions where FI is unreliable. Compared to FI, the FE method is also suitable for use with isotope tracer studies. One major advantage of the FE method is that the labeled biomass that develops as substrates decompose can be measured immediately after substrate addition, which is not possible with FI. In most situations, the FE method has become the standard technique for assessing microbial biomass, replacing FI (Mori *et al.* 2021).

### 4.2 Measurement of MB-N through Fumigation Extraction (FE) Method

MB-N is extracted post-fumigation into 2 M KCl, as depicted in Fig.1, and subsequently filtered through the Whatman-42 paper. A 10 ml aliquot of the filtrate is transferred to a 250 ml digestion distillation tube, to which 1 g of MgO is added. The sample is then processed using a Kjeldahl apparatus, with the inclusion of 2% boric acid (pH 4.5), and titrated with a standardized $H_2SO_4$ solution. Nitrate nitrogen ($NO_3$-N) is analyzed in the resultant distillate using Devarda's alloy, as per the methodologies outlined (Brookes *et al.* 1985) 8 ml of soil extract is treated with 2 ml of concentrated $H_2SO_4$ (d = 1.84), 0.2 g of Devarda's alloy to account for nitrates and nitrites, and 1g of a mineral catalyst (comprising 100 parts $K_2SO_4$, 10 parts $CuSO_4$, and 1part Se) in 75 ml digestion tubes. The mixtures undergo initial digestion at 110 °C for 70 minutes, followed by further digestion at 375 °C for 3.5 hours. After this, the mixture is placed into a distillation assembly and then titrated with either 0.1N HCl or 0.02N $H_2SO_4$ (color change to pink) calculate Extractable Nitrogen (EN). Total nitrogen content is then determined in 25 ml aliquots through steam distillation (Bremner and Mulvaney 1983; Badalucco *et al.* 1992). (Fig.1) shows fumigation followed by direct extraction into 0.5 M $K_2SO_4$ and 1M KCL, followed by MB-C using the potassium dichromate method and MB-N using the Kjhaldal method.

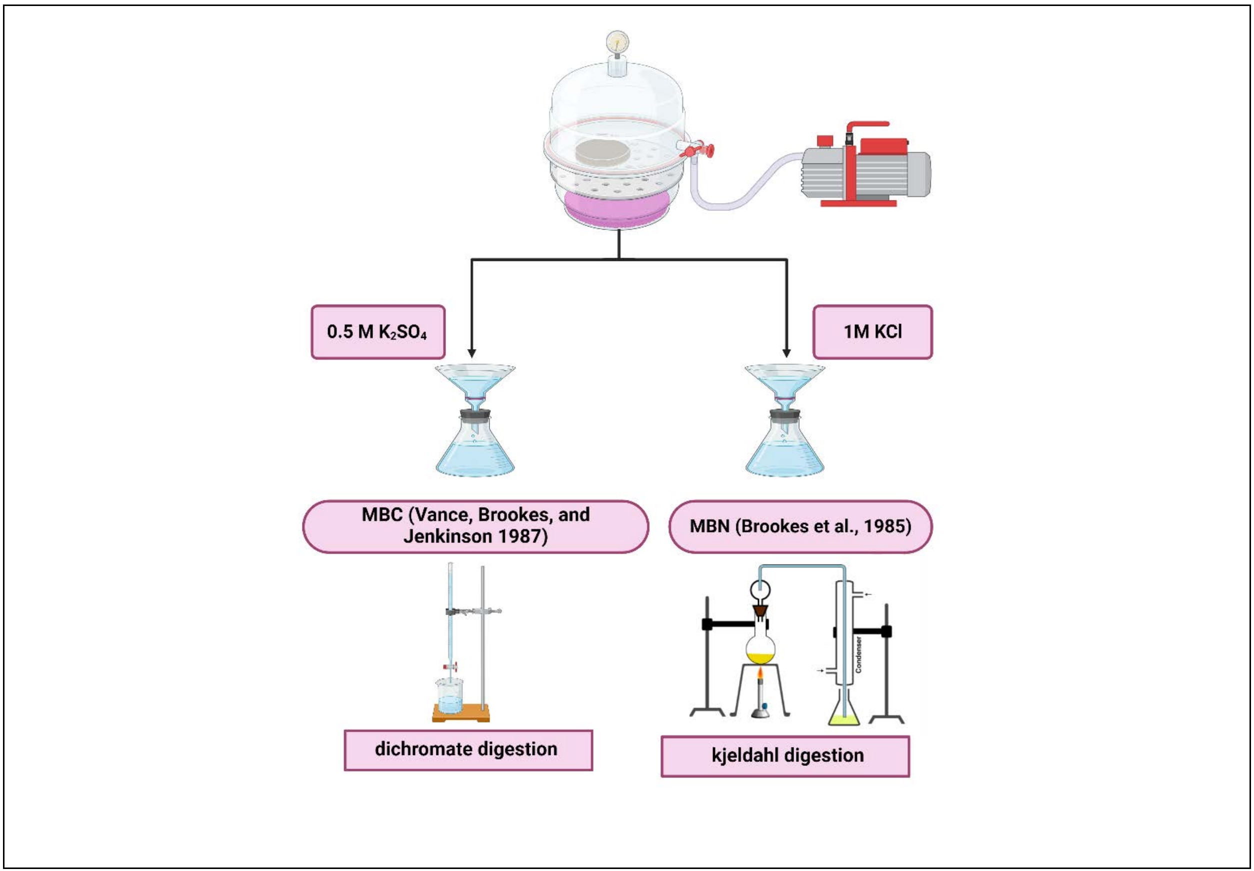


**Fig. 1: Extraction and Digestion methods for MB-C and MB-N**

## 5. ABIOTIC AND BIOTIC FACTORS AFFECTING MB-C AND MB-N TRANSFORMATIONS

### 5.1 pH

pH level is a crucial determinant that governs various soil functions. These include the composition and behavior of microbial communities, microbial functions, plant growth efficiency, and the spectrum of nutrients available in the soil for biological use (Kemmitt *et al.* 2006). The effect on pH regulation of carbon and nitrogen dynamics in soils was studied and found that soil microbial biomass carbon increases linearly with increasing pH (Meharg and Killham, 1990; Lu *et al.* 2022), It has been documented that prolonged pH adjustment in agricultural soil typically exerts negligible influence on soil microbial biomass carbon (SMB-C) as measured by the fumigation-incubation method. The findings showed that microbial biomass carbon increased with higher pH, especially in soils with a pH below 5. Respiration decreased in soils with a pH less than 4.5, and the respiration quotient rose in soils with a pH of 4 and below (Geisseler and Scow, 2014).

### 5.2 Heavy Metals

Heavy metals can negatively impact soil microbial biomass. Microbial biomass carbon as a percentage of soil organic C is a sensitive indicator of the effects of heavy metals on soil microbial biomass. A study by (Zeng *et al.* 2024), has shown that the soil microbial biomass carbon does not have significant relationships with soil heavy metal concentrations (Wang *et al.* 2009). (Dwivedi and Soni, 2011) revealed the negative correlation between soil microbial biomass and the presence of heavy metals. This suggests that elevated concentrations of heavy metals in soil can inhibit the growth and activity of microbial communities, which are crucial for nutrient cycling and soil health. Heavy metals may disrupt microbial cell membranes, interfere with enzyme function, or cause oxidative stress, leading to decreased microbial biomass. Understanding this relationship is vital for assessing the impact of soil contamination on microbial ecology and for developing strategies to mitigate the adverse effects on soil ecosystems.

### 5.3 Temperature

Temperature exerts a significant influence on soil microbial biomass. Research conducted by (Contin *et al.* 2000) revealed that microbial biomass carbon remains relatively stable across both arable and grassland soils at varying temperatures. Storage at lower temperatures increased soil microbial biomass carbon. Conversely, Islam *et al.* (2022) observed that temperate soils possess larger initial microbial biomasses compared to tropical soils. During the initial 50 days at 15 °C, the reduction in biomass is gradual for both soil types; however, at 35 °C, all soils exhibit a rapid decline in biomass within the same timeframe. Soil microbial biomass is affected by numerous factors, including soil moisture levels, plant species diversity, and land management strategies. The findings indicate that forest soils display the most robust soil health, succeeded by plantation, grassland, and agricultural soils in descending order. Forest and desert soils, subjected to persistent environmental stressors, demonstrate lower microbial biomass and consequently reduced activity under various climatic conditions, as reported by (Qu *et al.* 2023).

### 5.4 Microbial Community Composition

Plants secrete organic compounds into the soil via root exudates, which act as carbon sources for soil microbes. In exchange, these microbes perform crucial functions in nutrient cycling, including nitrogen fixation and mineralization, which promote plant growth. This symbiotic interaction between plants and microbes affects the soil's carbon and nitrogen availability. (Philippot *et al.* 2013) explored these complex interactions between plants and soil microbes, highlighting their significance in the nutrient-cycling process. The variety and makeup of soil microbial populations are pivotal in the cycling of carbon and nitrogen. Various microbial groups possess distinct capabilities for breaking down organic substances, fixing nitrogen, and facilitating other biogeochemical activities. Alterations in the composition of these microbial communities, which may be caused by land use changes or ecological disturbances, can impact the dynamics of soil carbon and nitrogen. (Ramirez *et al.* 2012) demonstrated the influence of microbial community shifts on soil nutrient cycling mechanisms. Microbial biomass constitutes 1 to 5% of Soil Organic Matter (SOM), with fungi making up about 90% of this biomass. These microbes can break down most organic materials. While it may not be entirely accurate, it is commonly believed that soil contains all necessary microorganisms to decompose any natural substances (and many man-made ones) and that they are collectively fail-proof. This belief is generally valid for numerous decomposition activities due to the vast functional redundancy within microbial decomposer communities. However, it's not always correct to assume redundancy for all specific functions in soils. For instance, the specialized relationship between plant hosts and their mycorrhizal partners suggests that such ubiquity cannot be presumed (Dixon and Tilston, 2010). Soil microbial diversity is influenced by interactions among different microbial species and with other soil organisms such as fungi, protozoa, and nematodes. These interactions affect carbon and nitrogen turnover rates and the efficiency of nutrient cycling processes. (Bardgett and Van, 2014) explored the role of soil biodiversity in regulating carbon and nitrogen dynamics and ecosystem functioning.

### 5.5 Predation and Grazing

Soil microbial communities can be influenced by predation and grazing by other soil organisms. For instance, bacterivorous nematodes prey on bacteria, affecting microbial biomass and activity levels. These interactions indirectly impact carbon and nitrogen cycling by influencing the structure and functions of microbial communities. Studies, conducted by (Gao *et al.* 2021), explored the effects of soil fauna on microbial communities and nutrient dynamics. Tropical grasslands, dominated by C4 grasses, could potentially serve as an important global carbon sink if moderate grazing increases SOC. Given the significance of grasslands in soil fertility and greenhouse gas reduction, further research on grazing's impact on SOC in tropical regions is crucial (McSherry and Ritchie, 2013).

## 6. MICROBIAL BIOMASS CARBON AS A SENSITIVE INDICATOR OF SOIL HEALTH

If SOC increases, Microbial Biomass Carbon (MB-C) also increases in a straight-line pattern. By using different ways to study the soil, we can better understand how big the microbial community is, how active it is, and how many different types of microbes are present (Stockdale and Brookes, 2006). C and N fluxes and the primary effects of extracellular enzyme production are depicted in Fig. 2 (Blagodatskaya and Kuzyakov, 2008). In cultivated, pasture, and woodland soils, this connection is typically strong. Compared to SOC, MB-C reacts more rapidly to alterations in soil management (Babur and Dindaroglu, 2020). In arable, grassland, and forest soils, this connection is typically strong. MB-C tends to react more swiftly to soil management changes than SOC. This is attributed to MB-C being a more transient carbon source that breaks down more easily than SOC. Changing a forest or grassland into a farmland result in a significantly larger decrease in MB-C compared to SOC (Zhang *et al.* 2023). Arable land management practices, such as tillage, can disrupt soil aggregates and release SOC into the atmosphere. The close relationship between MB-C and SOC, along with MBC's sensitivity to changes in soil management, renders MB-C a valuable indicator of soil health and sustainability. Monitoring MB-C levels allows us to observe the impact of various management practices on soil carbon cycling and nutrient availability. The addition of straw to soil has been shown to increase $CO_2$-C evolution and nitrogen mineralization without significantly affecting the total content of soil organic C and N. This increase is likely due to the decomposition of straw, which provides a source of organic matter and nitrogen for soil microorganisms, leading to the release of $CO_2$-C and nitrogen into the soil. Although the rise in $CO_2$-C evolution and nitrogen mineralization is notable, the overall soil organic C and N content remains largely unchanged. This indicates that straw decomposes rapidly, and the organic matter and nitrogen releases are not retained in the soil for an extended period. These findings suggest that adding straw to soil can effectively enhance the availability of organic matter and nitrogen for soil microorganisms. However, it is crucial to recognize that straw may not significantly influence the total soil organic C and N content. Rosswall and Paustian 1984, along with (McGill *et al.* 1986), suggest that variations in the microbial biomass size and activity within the soil can significantly influence crop yields, although these effects may take years to substantially modify soil properties. (Parr and Papendick, 1997) also noted that soil's physical and chemical traits greatly affect microbial biomass and activity, serving as indicators of soil health.

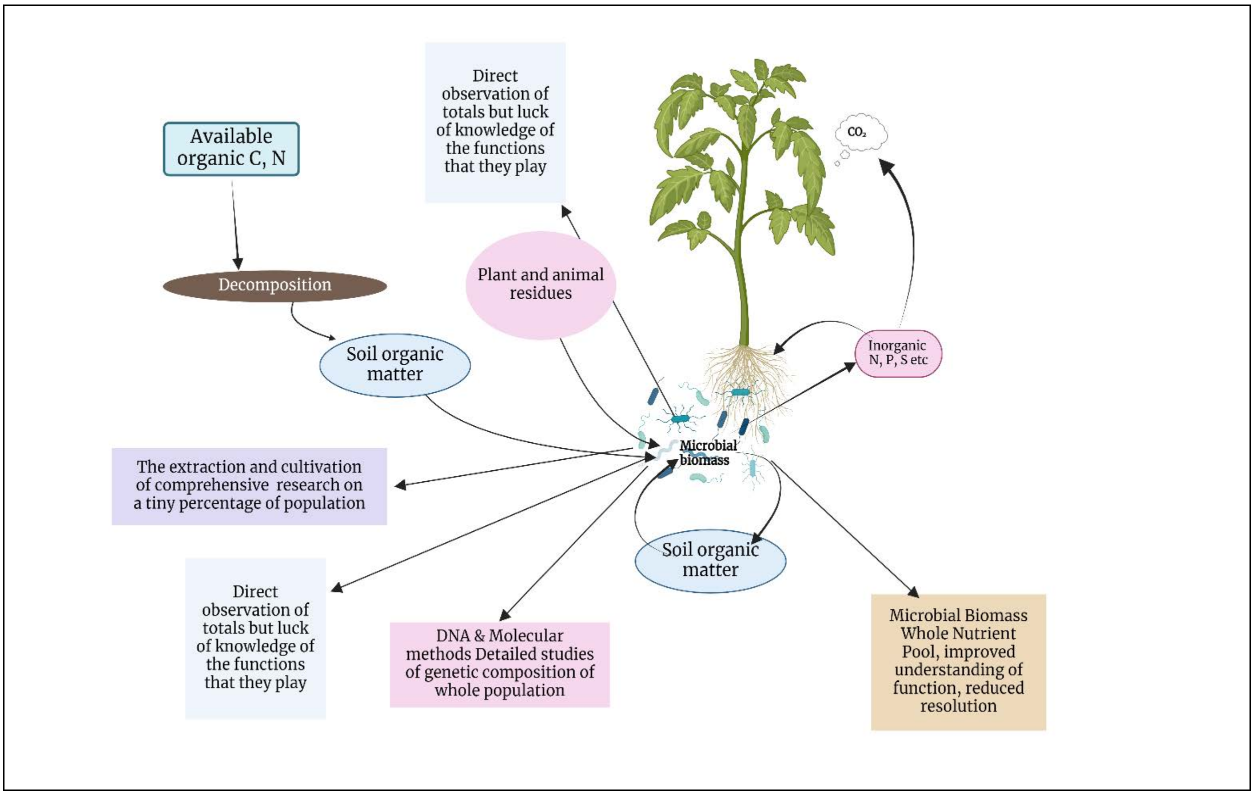


**Fig 2: Extracellular enzyme production**

Microorganisms act as both suppliers and storages for nutrients, meaning that shifts in microbial communities due to changes in soil conditions like moisture, organic carbon, nutrients, temperature, and pH carry important consequences for nutrient cycling. Even minor changes in soil conditions, such as degradation or erosion, can lead to notable biological and biochemical transformations in the soil (McGonigle and Turner, 2017). Numerous studies have documented soil microbial biomass across various forest ecosystems (citations from 1991 to 2003), yet data on its seasonal fluctuations within these environments is scarce (Diaz-Ravina *et al.* 1995). Research in a dry tropical deciduous forest near Udaipur, Rajasthan, India, has been conducted to examine these seasonal shifts in microbial carbon, nitrogen, and phosphorus, as well as the influence of non-living, physical, and chemical factors on this biomass. The soil components, viz., carbon, nitrogen, and phosphorus are crucial for plant growth and play a significant role in the cycling of materials. Additionally, different types of vegetation significantly influence soil organic carbon and total nitrogen levels (Zhang *et al.* 2023). In every type of vegetation studied, SOC was significantly higher in the top 0–20 cm layer compared to deeper layers, displaying a pattern where SOC and total nitrogen concentration decrease in an "inverted triangle" fashion from the surface down to 60 cm. This decline in concentration with increasing soil depth aligns with findings by (Fu *et al.* 2012) and (McGonigle and Turner, 2017), likely due to better aeration in the upper soil layers and the downward transport of nutrients.

## 7. CONCLUSION

Soil Microbial Biomass plays a pivotal role in nutrient cycling, organic matter decomposition, and overall ecosystem function. Its measurement serves as a valuable indicator for assessing soil quality and guiding management practices. Forest soils, abundant in microbial life, significantly contribute to the maintenance of ecosystem health. These microorganisms are essential for transforming organic matter into simple inorganic compounds, making them available for plant uptake. Their activities, particularly related to carbon, nitrogen, and phosphorus mineralization, are crucial for biogeochemical cycling. Beyond nutrient cycling, they also contribute to organic matter degradation, nutrient conversion, and supply. Processes like decomposition, leaching, humification, and mineralization affect nutrient availability and ecosystem productivity. Microbes, including bacteria, fungi, actinomycetes, protozoa, nematodes, earthworms, and other organisms, form the decomposer community. They break down complex materials, such as cellulose, hemicellulose, and lignin using extracellular enzymes. Despite constituting a small fraction of total soil organic matter (1-4%), microbial biomass serves as a labile reservoir for essential plant nutrients (N, P, S) in arable soils. Measuring soil microbial biomass carbon provides insights into soil quality, reflecting microorganisms' role in carbon availability and bridging the gap between soil chemistry and vegetation assessments.

The sensitivity of MB-C due to its close relationship with SOC makes it a very valuable indicator of soil health and sustainability, which greatly enhances the fertility of the soil, ultimately improving crop yields. The climatic variations in the forest as well as arid to hyper-arid regions have increasingly severe effects on C/N ratios which have a direct impact on the concentration and cycling of nutrient elements through microbial activities. Thus, the change in the nutrient status of any soil takes a very long time for their determination but such changes could be determined very rapidly under laboratory conditions where microbial biomass could serve as an early indicator of such changes in almost every type of soil. Therefore, studies on microbial biomass have been very significant for understanding the transformations of nutrient elements, particularly C, N, and P, and for determining the soil quality and nutrient status.

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## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.



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