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Review Article

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Transformation and cycling of major nutrient elements in soils and their fractionation influenced by land use and management practices

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ABSTRACT

Soil nutrient fractionation is fundamental process in determining soil fertility, nutrient cycling, and crop productivity. Major nutrient elements, *viz.* carbon (C), nitrogen (N), phosphorus (P), potassium (K), and sulphur (S), exist in various forms in soil and undergo dynamic transformations due to biological, chemical, and physical processes. Factors including soil texture, pH, moisture, temperature, and microbial activity influence these nutrient transformations. Soil aggregates and microbial communities help in nutrient retention and cycling, as well as impact on plant nutrient uptake. Nutrient content may vary across different soils, like saline, acidic, and calcareous soils, which emphasizes the complexity of nutrient dynamics and the need for specific management approaches. Nowadays, researchers use different methods to determine nutrient fractions in soil. These methods help to identify nutrient pool and nutrient availability in soil. Land use and management practices including tillage, residue incorporation, and fertilization influence nutrient fractionation. Sustainable soil management practices like conservation agriculture, green manuring, and biochar application help maintain nutrient balance, improve soil health, and enhance long-term agricultural productivity. This review highlights current information on the fractionation of C, N, P, K, and S in soil, their transformations, and the role of microbes in their cycling. It also investigates the effects of land uses and management practices on nutrient fractions and soil fertility. Advancing this field requires an integrated approach that links microbial processes with multi-nutrient cycling to create predictive models for sustainable soil management. Understanding these processes is essential for developing sustainable agriculture strategies that increase nutrient availability and minimizes environmental damage.

KEYWORDS: Nutrient fractionation, Soil aggregate, Nutrient transformation, Microbial activity, Land use, Soil management

INTRODUCTION

The soils of the world contain many essential nutrient elements for plant growth, and these nutrients come from many sources, like soil, atmosphere, water, decomposition of organic matter, weathering of rocks, etc. Some nutrients are found in trace amounts in the environment, while others show a great diversity of inorganic and organic species, ranging from ions in solution to very stable inorganic and organic compounds, and are termed as nutrient fractions. To determine the concentrations of individual nutrients in distinct soil portions or the relative abundances of different elemental forms in a given soil, it is common practice to do nutrient fractionations (Shuman, 1985). The majority of the fractions play important roles in both abiotic and biotic processes. Labile nutrients, like ammonium, nitrate, soluble phosphate, soluble potassium, and sulphate, are readily available for plants, supporting immediate growth. In contrast, non-labile nutrients, found in organic compounds (humus) and minerals, provide long-term soil fertility. These forms, bound to soil particles, release slowly through weathering and microbial activity, sustaining plant nutrition and contributing to overall ecosystem nutrient cycling.

In soil, carbon (C) originates from plant residues, root exudates, and decomposed organic materials, contributing to soil fertility. About 80% of the total terrestrial C storage can be found in soil, making it an important part of the global C cycle (Lal, 2008). Surface soil has a greater concentration of soil organic carbon (SOC) than deeper layers, and it is about 90% of the total SOC (Wang *et al.*, 2023). Soil organic matter (SOM) is a storehouse of nutrients, mostly related to nutrient fractions, and the main source of nitrogen (N), sulfur (S), and phosphorus (P). N is derived from organic matter decomposition, atmospheric deposition, and N_2-fixing bacteria that convert atmospheric N into plant-available forms. P is sourced from the weathering of minerals, organic residues, and microbial activities, while potassium (K) is released through mineral weathering and organic matter breakdown. In soil, S is obtained from organic matter decomposition and atmospheric deposition. Organic substances typically pair with molecules that decompose quickly to slowly, but inorganic compounds tend to partner with amorphous and crystalline forms of minerals (Hedley *et al.*, 1982). The organic matter in soil breaks down into labile and stable fractions based on their respective densities. The only necessary plant nutrient that is not released by the weathering of minerals in soils is N, with the possible exception of minor amounts of geogenic (mineralogically fixed) N but P, K and S are originally introduced into soils when nutrient-containing minerals in parent rock (10^{-2} g P kg^{-1}, 331.5 g K kg^{-1} yr^{1}) are weathered (Zhu *et al.*, 2008; Kruse *et al.*, 2015).

The plant's available exchangeable forms of nutrients are retained on the colloid particle surfaces of soil and released slowly over time. In contrast, the non-exchangeable forms of ions are locked in the silicate minerals of soil, making them inaccessible to plants (Bilkis *et al.*, 2014). Although some microbes can get molecular C, N, P, and S, all other forms of life must rely on combined molecules to function normally. When comparing N and C levels, Read and Ridgell (1922) discovered that N was more stable than C. Inorganic N-P-K-S are recycled back into the soil solution through decomposition and mineralization (Wang & D'Odorico, 2013). Labile P is controlled by biological processes, and organic P recycling is crucial to soil P supply (Stewart & Tiessen, 1987). Soil solution K is the focal point for the nutrient source of the plant, as the plant absorbs K quite easily.

There has been a lot of study on soil nutrients over the years, but most of it has focused on SOC fractions, organic and inorganic N-P-K-S compounds. Understanding the movement of elements between chemical forms in response to shifting soil conditions and their distribution in the environment might lead to the development of more effective extractants that selectively remove elements in accordance with the amounts taken up by plants. Despite the knowledge of different forms of nutrients in soil under different agricultural systems, there is still no consensus on the absolute forms and availability of nutrients in nutrient cycling. This review deals with different forms of soil nutrients, especially C, N, P, K, and S, their fractionations as influenced by different land uses and their balance through management practices for sustainable agriculture.

NUTRIENTS AND PLANT RELATIONS

Nutrient forms and their availability in soil significantly impact plant growth and development; on the other hand, nutrient deficiencies or imbalances can limit crop production and reduce yield and quality. So, the proper amount of nutrients is essential for maximizing crop productivity and ensuring high-quality harvests. For plants, both macronutrients and micronutrients are required. Important cellular components like proteins and nucleic acids require large amounts of macronutrients like N, P, K, and magnesium (Mg). In addition to being macronutrients, C, hydrogen (H), and oxygen (O) are also necessary for the synthesis of larger organic molecules. On the other hand, micronutrients like iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu), which function as cofactors for enzyme activity, are needed in very small amounts (Morgan & Connolly, 2013). SOC is essential for soil health, increasing carbon storage, improving fertility, and promoting plant growth. K is necessary for crucial processes in plants, including enzyme activation, charge equilibrium, and osmotic regulation. N, P, and S are responsible for protein synthesis and the production of essential vitamins and cofactors (Kertesz & Mirleau, 2004). In the majority of plant nutrition experiments, the impact of a single nutrient on plant growth has been studied (Toor *et al.*, 2021). In Table 1, the primary function of the major nutrient components in plants' bodies has been outlined as follows (Foth, 1978).

Table 1: Major role of C, N, P, K, and S in the plant body

Nutrient	Available form for plants	Key roles in the plant body
Carbon (C)	CO_2 (atmospheric)	- Primary building block of organic compounds (carbohydrates, lipids, proteins, nucleic acids) - Essential for photosynthesis - Structural components of cellulose, lignin, and starch
Nitrogen (N)	NO_3^- (nitrate), NH_4^+ (ammonium)	- Key component of amino acids, proteins, and enzymes - Essential for chlorophyll synthesis - Integral part of nucleic acids (DNA & RNA) and coenzymes (e.g., ATP, NADH) - Promotes vegetative growth (leaves, stems) and overall plant vigor
Phosphorus (P)	HPO_4^{2-}, $H_2PO_4^-$, PO_4^{3-} (phosphates)	- Critical for energy transfer (ATP, ADP) in metabolic processes - Structural role in nucleic acids (DNA & RNA) and phospholipids (cell membranes) - Enhances root development, flowering, and seed formation - Facilitates N fixation in legumes
Potassium (K)	K^+ (potassium)	- Regulates stomatal opening/closing - Activates enzymes in protein & carbohydrate metabolism - Improves drought and disease resistance - Essential for photosynthesis, sugar transport, and starch formation - Enhances fruit quality (size, color, taste)
Sulphur (S)	SO_4^{2-} (sulphate)	- Components of amino acids (cysteine, methionine) and proteins - Vital for enzyme activation (e.g., coenzyme A) - Important for nodule formation in legumes

Optimal nutrient supply is necessary for crop production. On the other hand, nutrient deficiencies result in visible symptoms in plants, such as chlorosis (yellowing of leaves), stunted growth, and reduced crop yield. For example, yellow leaves and stunted plant growth can be due to N deficiency, while P deficiency can cause purple discoloration and reduced root development in plants. K deficiency leads to leaf edge necrosis (scorching), and S deficiency causes yellowing of young leaves (similar to N, but starts in new growth). Interestingly, the relationship between nutrient availability and plant health is not linear. Excess nutrients can be just as detrimental to plant health as deficiencies. Over-fertilization, especially with N and K, leads to nutrient imbalances and environmental issues like nutrient leaching, pollution, and eutrophication. Additionally, excessive nutrients may interfere with plant physiological processes, negatively affects growth, and reduce crop quality. Researchers have established a growth response curve (Figure 1) to understand the relationship between plant growth and nutrient concentration in soil where it is shown that growth is at its peak and is largely unaffected by changes in nutrient supply (adequate range); growth increases with increasing nutrient supply (deficit range); and growth decreases with increasing nutrient supply (toxicity range) (Römheld, 2012).

SOIL AGGREGATE ASSOCIATED NUTRIENT STOCKS

Soil aggregates are structural components that regulate the dynamics of SOM, nutrient cycling, porosity, and aeration within the soil profile and also have an impact on plant and microbial populations, water infiltration, and erosion (Bossuyt *et al.*, 2005). Primary soil particles (sand, silt, clay) are architecturally arranged with SOM and inorganic cementing agents to form soil aggregates. Two types of soil aggregates are found i.e., macroaggregates (>2.0, 2.0-0.85, 0.85-0.30 mm) and microaggregates (0.30-0.15, 0.15-0.053 mm) (Jahangir *et al.*, 2021). Organic materials, such as humic substances, act as a cementing agent for the stabilization of microaggregates. In field root deposits, plant roots act as glue, and microaggregates are bound together to form macroaggregates. Similar to microaggregates, macroaggregates are formed and stabilized by polysaccharides, glomalin, fungal hyphae, fine roots, and bacterial cells (Denef & Six, 2005). As fundamental components of soil structure, soil aggregates affect many physicochemical parameters, stabilizing and protecting SOC and nutrients (Sarker *et al.*, 2018). The nutrient storage capacity of soil aggregate is critical for nutrient cycling and stability; 90% of SOC is stored in aggregate in the topsoil (Rabot *et al.*, 2018), and macro-aggregate is the most important portion for storing SOC (Rabot *et al.*, 2018; Kurmi *et al.*, 2020). Soil aggregate sizes affect nutrient retention and turnover. Mikha and Rice (2004) and Kong *et al.* (2005) found that macroaggregates contain more C, N, S, and P than microaggregates.

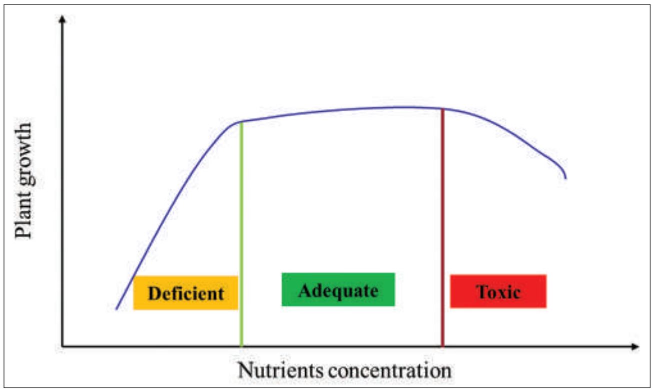

Figure 1: Relationship between nutrients and plant growth (Römheld, 2012)

The dynamics of SOM may also be influenced by nutritional stoichiometry, where C: N, C:P, and N:P were higher in 0.053 mm size aggregate, SOC had a positive significant relationship with TN for all aggregates except 0.0053 mm, and SOC had a strong positive relationship with TP for all aggregates (Wang *et al.*, 2022). SOM is the sole source of SOC, and it is physically protected in aggregates. SOC is stabilized through physicochemical means by inhibiting its decomposition (Gunina & Kuzyakov, 2014). Different aggregate components exhibit different nutrient storage capacities. For instance, Zhang *et al.* (2017) investigation indicated that the contribution of macro-aggregate (>0.25 mm) to the SOC storage was larger than that of other aggregate fractions. Xie *et al.* (2017) discovered that the SOC and TN were primarily fixed in micro-aggregate (0.25 mm) through a 21-year field fertilization experiment because of the increased amount of TN in smaller macroaggregates (0.85-2 mm) in comparison to other aggregates. Macroaggregates larger than 2 mm contained less TN than the 0.85-2.00 mm size class. This suggests that the larger macroaggregates are made up of smaller microaggregates, which allow more oxygen to move within them due to higher porosity and microbial activity. As a result, nitrogen is more actively mineralized in these aggregates. Overall, smaller macroaggregates tend to hold more TN in soil. It was found that in both native and cultivated soils, the mineralization rate of C, N, and S was higher in macroaggregates than in microaggregates (Gupta & Germida, 1988). Soil quality and fertility are closely linked to both the quantity and stability of soil aggregates. SOC plays a vital role in enhancing fertility, boosting crop yields, and improving the formation and stability of water-stable aggregates. Fertilization positively affects the accumulation of SOC, TN, and TP within soil aggregates, with the 2-0.25 mm and 0.25-0.053 mm fractions being the main contributors to their storage. The greater percentage of 2 to 0.25 mm and 0.25 to 0.053 mm fractions could be the explanation for this (Mustafa *et al.*, 2020). When it came to the TN stock, there was no discernible difference between fertilization treatments for either the 2 to 0.25 mm or the 0.25 to 0.053 mm fraction, even though Craswell *et al.* (1970) reported identical outcomes, and they likely have comparable N mineralization rates. Zheng *et al.* (2018) showed that no significant relationship was found in C stock in microaggregates with depths, indicating that the largest macroaggregates (> 2.00 mm) were responsible for SOC stock. Organic carbon is more labile in macroaggregates than in microaggregates (Zhou *et al.*, 2020). In macroaggregates, SOC is more susceptible to change than in microaggregates (Zhou *et al.*, 2020), which may cause maximum accumulation of SOC in smaller microaggregates than in macroaggregates. Aggregates provide physical protection to SOM and make it stable to hinder its decomposition (Du *et al.*, 2013; Gunina & Kuzyakov, 2014). Yang *et al.* (2007) and Jahangir *et al.* (2021) found that macroaggregates mineralize more TN than microaggregates. Larger aggregates caused more diffusion. Macroaggregates had lower TN than microaggregates because macroaggregates are made up of microaggregates and oxygen is present within pores, causing mineralization (Jahangir *et al.*, 2021). Sainju *et al.* (2007) found a higher amount of available P in microaggregates than in macroaggregates due to rapid decomposition, but Kong *et al.* (2005) stated higher available P in macroaggregates. The production of soil aggregates is a method for C sequestration as well as increasing the soil's C and N input to plant growth. Carbon sequestration, along with soil's N contribution to plants, is mechanized by the formation of soil aggregates.

The optimal aggregate with a diameter >0.25 mm has a good capacity for aeration, fertilizer and water conservation (Six & Paustian, 2014). According to Wang *et al.* (2022), the macro-aggregate of >2 mm was shown to be closely related to SOC, TN, and TP (Figure 2), showing a trend in the supply of nutrients in the aggregate. Various-sized soil aggregates have different effects on N availability and transformation (Chen *et al.*, 2001). The macroaggregate (>0.25 mm) contributed more to the SOC accumulation than the other aggregate fractions (Mustafa *et al.*, 2020). Additionally, the aggregated SOC, TN, and TP content had a V-shaped change trend with decreasing particle size (Qu *et al.*, 2019), and some of them displayed a rising tendency (Pan *et al.*, 2019). The distribution of a soil aggregate is altered by the amount of nutrients present, which also increases soil fertility and affects the stability of the aggregate (Spohn & Giani, 2010; Zhong *et al.*, 2021). Different aggregates' capacities to deliver and retain SOC and nutrients vary depending on their particle size (Arai *et al.*, 2013). According to a study (Yao *et al.*, 2019), most of the SOC and TN are concentrated in the macroaggregates of the surface layer. Studying the composition and distribution of soil aggregates in agricultural soils is essential for understanding how nutrients are stored and cycled. Such research helps clarify how SOC and other nutrients are distributed among different aggregate size fractions and reveals the mechanisms that regulate nutrient interactions and balance within the soil structure.

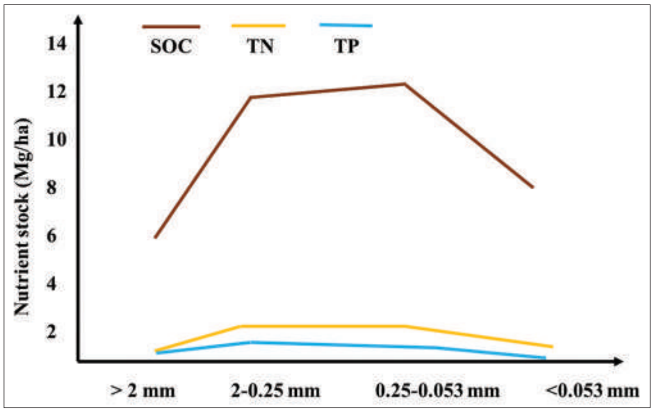

Figure 2: The stock of SOC, TN, and TP within soil aggregates in China (Wang et al., 2022)

CHANGES IN THE NUTRIENT FORMS AND THEIR TRANSFORMATION

Nitrogen

N is one of the essential nutrients for plants. Most of the N plants uptake comes from applied fertilizers rather than the soil itself (Omar *et al.*, 2020). In favorable conditions, plants can absorb 50-70% of fertilizer N, where 2-20% is lost to the atmosphere, 15-25% is retained on organic particles and clay minerals, and 10% is leached into groundwater and surface waters (Gray, 2008). Bulk density, soil clay content, organic matter, pH, climate, vegetation, terrain topography, and human activity are significant factors determining the N content of soil (Bechmann, 2014; Vaverková & Adamcová, 2014). The most active N pools, such as ammonium-N (NH_4-N), amino sugars, and amino acids, are important sources of organic N that can be hydrolyzed and potentially converted into plant-utilizable forms. These pools are important contributors to the decomposition of organic N fractions in the soil, releasing available N forms (NH_4^+ and NO_3^-) (Khan *et al.*, 2001; Sharma *et al.*, 2001). Soil organic N fractions are important for estimating soil organic N decomposition and its impact on N availability (Wander, 2004). The transformation of N compounds in the soil is affected by various factors, such as soil properties (pH, exchange capacity), soil reactions, and farming practices, all of which differ based on the level of technological advancement in farming (Gworek *et al.*, 2021). Soil N transformation is closely tied to organic carbon transformation. Factors affecting decomposition and synthesis of soil organic compounds, including humus, also influence the content of SOM and associated N. Temperature and soil moisture strongly impact these microbiological processes of N (Gworek *et al.*, 2021). Low temperatures can delay the hydrolysis of urea into ammonium form, while high temperatures and good humidity can increase N losses as ammonia. The changes in nutrient form in soil also depend on the soil heterogenic environment and agrotechnical treatments like cultivation procedures, fertilization techniques, or plant protection treatments, etc. Mineralization of organic N compounds in the soil environment leads to the formation of ammonium, which is the primary form of N available to plants (Długosz & Piotrowska-Długosz, 2016). Ammonium ions in the soil can undergo nitrification, converting them into nitrates, which are mobile and can be leached under heavy precipitation. Denitrification under anaerobic conditions can result in the release of N gases such as nitrous oxide (Mitchell *et al.*, 1998; Gnida *et al.*, 2016; Sosulski *et al.*, 2017). Dissimilatory nitrate reduction to ammonium (DNRA), also known as nitrate/nitrite ammonification, occurs in anaerobic respiration by chemoorganoheterotrophic microbes, using nitrate as an electron acceptor for organic matter oxidation (Kraft *et al.*, 2011; Lam & Kuypers, 2011). Leaching causes nutrient loss from the soil profile. The soil N cycle can be presented as follows (Figure 3).

Phosphorus

P is found in soils in a broad spectrum of organic and inorganic compounds, which vary in their bonding strengths, stability, and how easily they can be used by living organisms (Crews & Brookes, 2014; Hussain *et al.*, 2022). Inorganic P compounds in soil, such as phosphate ions and their complex forms, are often bound to soil particles and require processes like weathering or microbial activity to become accessible to plant roots. The transformation of P in soil is given below (Figure 4).

Organic P compounds, derived from decomposed organic matter, range from simple esters to complex molecules and need enzymatic activity by soil microorganisms to break them down into plant-available forms. Organic P constitutes 15-50% of total soil P (Shrivastava *et al.*, 2018), primarily existing as inositol phosphates (the most stable form), phospholipids (from cell membranes), and nucleic acids (from DNA/RNA). Its concentration varies depending on environmental factors like rainfall, temperature, and land use patterns. In acidic soils, P is

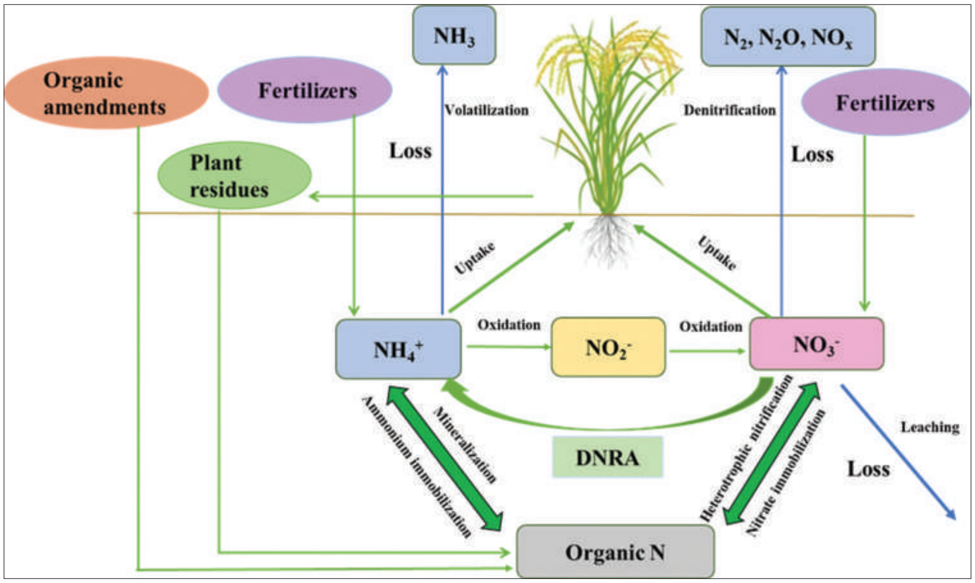

Figure 3: The soil internal N cycle with nitrification, mineralization, ammonium immobilization, nitrate immobilization, dissimilatory nitrate reduction to ammonium (DNRA), heterotrophic nitrification, and plant uptake (Norton & Ouyang, 2019)

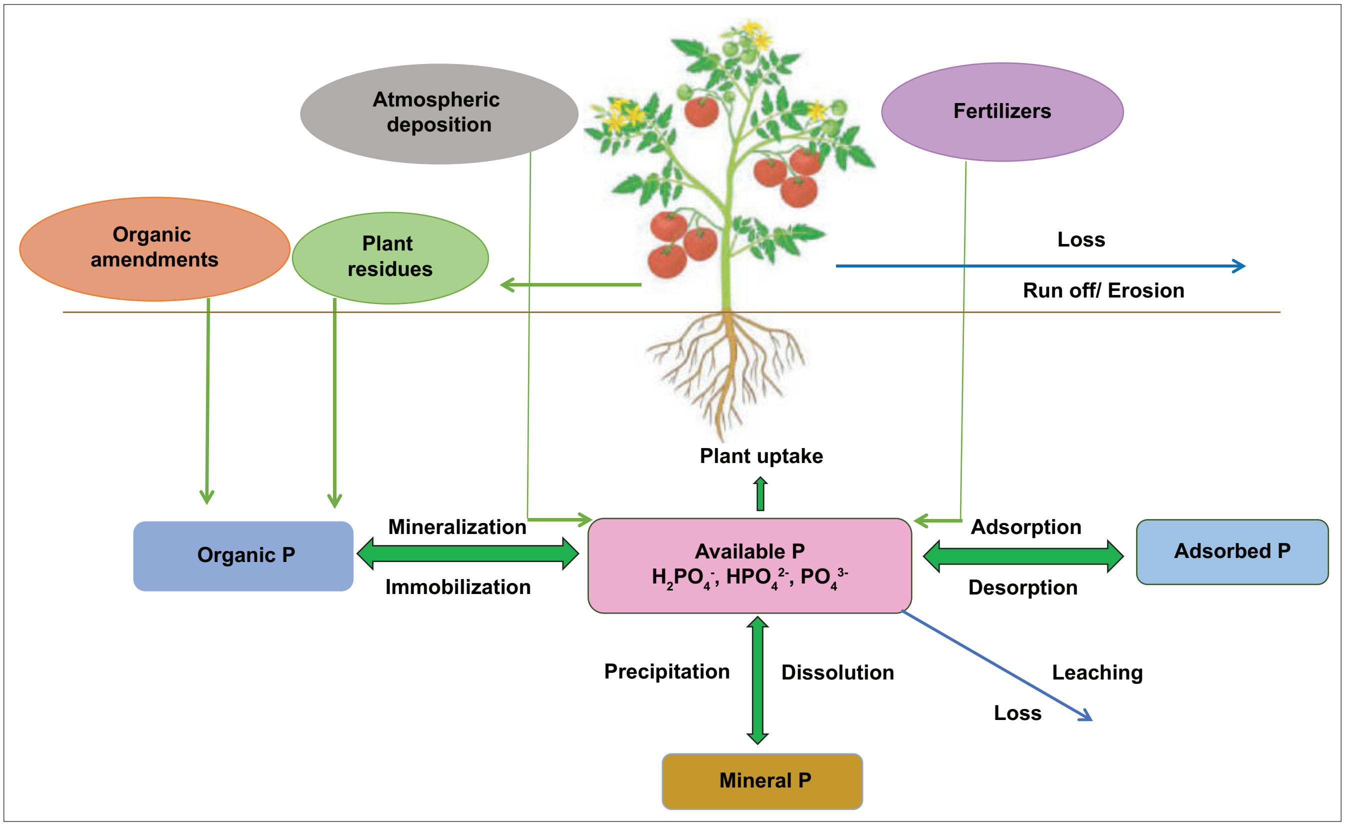

Figure 4: Transformation of P in agricultural soil

strongly retained by Fe and aluminum (Al) oxides (sesquioxides), while in alkaline calcareous soils, calcium carbonate ($CaCO_3$) plays the dominant role in P adsorption. Some organic P is also associated with bacterial cell walls (Shrivastava *et al.*, 2018). These retention mechanisms significantly influence P availability for plant uptake.

Changes in soil P content have an impact on the biogeochemical cycles of nutrients and play an important role in improving crop growth and yield (Shen *et al.*, 2011; Haque *et al.*, 2023). Soil transformations, including mineralization, immobilization, and sorption-desorption processes, influence the availability of P for plants. Total P content in soil typically ranges between 25 to 50 ppm (Liu *et al.*, 2017). However, only about 0.1% of this total P exists in forms readily available for plant uptake and the majority (99.9%) remains bound in insoluble fractions, either as organic compounds (like inositol phosphates, phospholipids, and nucleic acids) or as inorganic minerals that are chemically fixed by soil components (Liu *et al.*, 2017). The rate at which P is absorbed and released by the soil is greatly influenced by factors such as soil type, texture, pH, organic matter content, as well as the availability of sorption surfaces provided by calcium (Ca), Fe, and Al compounds (Brady & Weil, 1999). Inorganic soil P (Pi) exists in different forms with varying availability to plants. These include 1) labile Pi ($NaHCO_3$-extractable), which is readily available, 2) moderately available forms (NaOH-extractable and HCl-extractable), and 3) non-labile fractions that are tightly bound or occluded within minerals (Kashem *et al.*, 2004). The most stable forms are either chemically bound to iron (Fe-P), aluminum (Al-P), and calcium (Ca-P) surfaces or trapped within iron oxide structures (Residual-P) (Hussain *et al.*, 2022).

P application in soil triggers various biogeochemical processes, including changes in microbial activities and the mineralization of organic P into inorganic Pi form (Kritzler & Johnson, 2010). Combined N and P applications affect soil processes in several ways. Nitrification changes soil pH and influences the formation of organic P. It also increases the plant's demand for P. Additionally, N application mobilizes Fe and Al, which can bind with P on soil surfaces. This process converts easily available P (both organic and inorganic) into forms that are less accessible to plants (Carreira *et al.*, 2000; Vitousek *et al.*, 2010). High P-application rates reduce plant uptake efficiency, impacting plant growth. P fixation occurs when P input exceeds plant P uptake (Hussain *et al.*, 2022). Leaching losses of P are significant in certain soil types and with high organic manure input.

Potassium

K undergoes dynamic transformations among different fractions in the soil that influence its availability for plant uptake. These fractions include water-soluble (soil solution) K (0.50%), exchangeable K (1.00%), non-exchangeable (fixed) K (1-10%) and structural mineral K (~90-98%) (Figure 5) that exist in a state of dynamic equilibrium (Kaur, 2019). The availability of these forms can be influenced by various physical, chemical, biological, and climatic factors. The primary sources of soil K are potassium-bearing minerals such as micas and feldspars. These minerals weather over time to release K into more plant-accessible forms (Uribe & Cox, 1988). However, the majority of total soil K is structurally bound in minerals and secondary clays (illite), which makes K largely unavailable for immediate plant use (Sardi & Csitari, 1988). The transformation between K fractions is governed by multiple soil properties including clay mineralogy, cation exchange capacity (CEC), pH, moisture, and competing cations (Zeng & Brown, 2000; Barre *et al.*, 2008). Soils rich in 2:1 clay minerals (e.g., vermiculite and illite) generally exhibit strong K fixation. In some soils, applied K becomes trapped in the interlayer spaces of clay particles, which reduces its short-term availability (Scott & Smith, 1987). For instance,

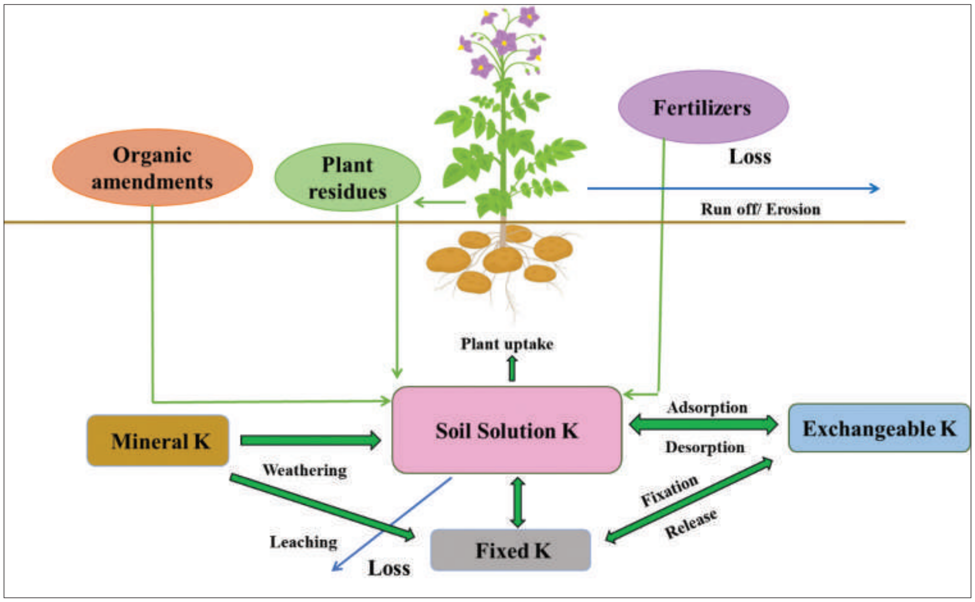

Figure 5: Transformation of K in agricultural soil

studies have shown that up to 92% of added K fertilizer can be fixed in certain soils (Doll & Lucas, 1973). Because of this, farmers sometimes need to apply very large amounts of K (e.g., 1,600 kg K/ha) to meet crop demands (Doll & Lucas, 1973).

When soil K concentration decreases, the fixed K may slowly release into the soil solution, but it's often too slow to meet plant growth needs. This process is not enough for crop requirements during rapid growth stages (Cox *et al.*, 1999). The rate of K release from fixed and mineral pools depends on the rate of weathering, soil mineral composition, exchange properties of the soil and environmental conditions such as wetting-drying cycles (Lalitha & Dhakshinamoorthy, 2014). Additionally, agricultural practices, including crop removal, fertilization, and organic matter management, significantly influence K cycling and long-term availability (Singh *et al.*, 2002). To manage K more effectively, it is important to understand how it changes in the soil. Strategies such as balanced fertilization, the use of K-mobilizing biofertilizers, and the incorporation of organic amendments can enhance K availability and reduce fixation losses (Rubio & Gil-Sotres, 1997). By considering some soil-specific factors like clay type and CEC, farmers can improve K use efficiency and sustain crop productivity in diverse agricultural systems.

Sulphur

S exists in various organic and inorganic forms in soil. These forms undergo dynamic transformations that determine their availability for plant uptake. Though plants primarily absorb S as sulphate (SO_4^{2-}), more than 90% of total soil S is present in organic forms (Sharma *et al.*, 2014). The inorganic fraction, mainly SO_4^{2-}, constitutes less than 10% of total S, and only ~1% is readily soluble and bioavailable (Freney, 1986). In well-drained agricultural soils, SO_4^{2-} levels are typically below 25 ppm, where S-deficient soils contain less than 10 ppm (Brown, 1982). Organic S makes up more than 75% of the total S and mainly includes ester sulphates (with C-O-S bonds) and carbon-bonded S (with C-S bonds) (Germida *et al.*, 2021). Microbial biomass contributes 0.9-2.6% of organic S and plays a key role in mineralization (Chapman, 1987). Inorganic S exists either in soil solution, adsorbed onto colloids, or co-precipitated with minerals (Kulhánek *et al.*, 2016). Under aerobic conditions, sulphate is the most stable form. But its retention depends on soil pH, clay content, and competing anions (Eriksen, 2009).

When microbes mineralize organic S, they release sulphate as a byproduct (McGill & Cole, 1981). Biochemical processes (enzymatic hydrolysis) break ester sulphates, while geochemical processes (e.g., adsorption, precipitation) regulate sulphate availability. In waterlogged soils, sulphate can be reduced to hydrogen sulphide (H_2S), which makes S loss in gaseous form (Brown, 1982). Conversely, oxidation of sulphides in aerobic zones replenishes sulphate pools. Soil properties significantly influence S dynamics. Soil organic matter serves as the primary S reservoir, with a slow microbial-mediated mineralization rate (Freney, 1967). Acidic conditions of soil promote sulphate adsorption, and sandy textures increase leaching losses. Intensive agricultural practices have accelerated S depletion through crop removal and imbalanced fertilization, which makes it necessary to take improved management strategies to maintain soil S balance (Balík *et al.*, 2009). These factors collectively regulate the transformation between organic and inorganic S pools and ultimately determine plant-available sulphate levels in agricultural systems. The transformation of S in soil is presented in Figure 6.

Soil Organic Carbon

Soil contains roughly two to three times more carbon than the atmosphere and serves as one of the largest terrestrial reservoirs of organic carbon (OC). According to Batjes (1996), approximately 1462-1584 petagrams (Pg) of carbon are stored within the top 100 cm of soil. SOC is generally categorized into three main pools: i) the active pool, which cycles over weeks; ii) the slow pool, with turnover times spanning decades; and iii) the passive pool, which can remain stable for thousands of years. The active pool is made up of readily oxidizable materials, such as the microbial biomass and its metabolites (Schnürer *et al.*, 1985). It is largely controlled by climate and residue inputs, which provide a nutrient source for plants (Schnürer *et al.*, 1985). The slow and/or very slow pools contain moderately decomposable material within macro- and microaggregates and particulate organic carbon (POC) (Parton *et al.*, 1987). The passive or recalcitrant pool includes stable C formed from the turnover of microbial and slow SOC that are chemically resistant to, or protected from, further microbial degradation (Schimel *et al.*, 1994). C stored in soil can be both labile and stable (Figure 7). Labile SOC fractions include plant-associated forms such as light fraction organic carbon (LFOC), POC, and dissolved organic carbon (DOC), along with microbial-associated forms such as microbial biomass carbon (MBC), easily oxidized carbon (EOC), and mineral-associated organic carbon (MOC). On the other hand, stable carbon mainly consists of heavy fractions of organic carbon (HFOC). Labile fractions undergo rapid changes and restoration, while stable form contributes to long-term storage of carbon. Total organic carbon (TOC) in undisturbed soils is influenced by the quantity and quality of plant litter, which serves as long-term soil cover. This enhances TOC levels and reduces carbon loss. SOC stability is also influenced by organo-mineral interactions, where metastable intermediate organo-metal complexes formed by chelation of organic acids with Fe^{3-} and Al^{3-} decrease decomposition and enhance carbon storage (Six *et al.*, 2002). The amount of carbon that can be added to soil depends on the total yearly carbon uptake by all plant species growing in that area. On the other hand, SOC depletion depends on chemical oxidation, leaching, and erosion (Jong & Kachanoski, 1988).

SOC fractions vary in turnover rates and responses to environmental changes. The ratio of active organic carbon to TOC is relatively small but serves as an indicator of changes due to environmental alterations and soil management (Jha *et al.*, 2012; Sahoo *et al.*, 2019). Active carbon fractions play a critical role in biological and chemical soil processes, facilitating nutrient cycling and storage (Simard *et al.*, 2001; Sun *et al.*, 2014). Soil organic matter (SOM) is stabilized by binding with silt and clay particles, which helps form micro- and

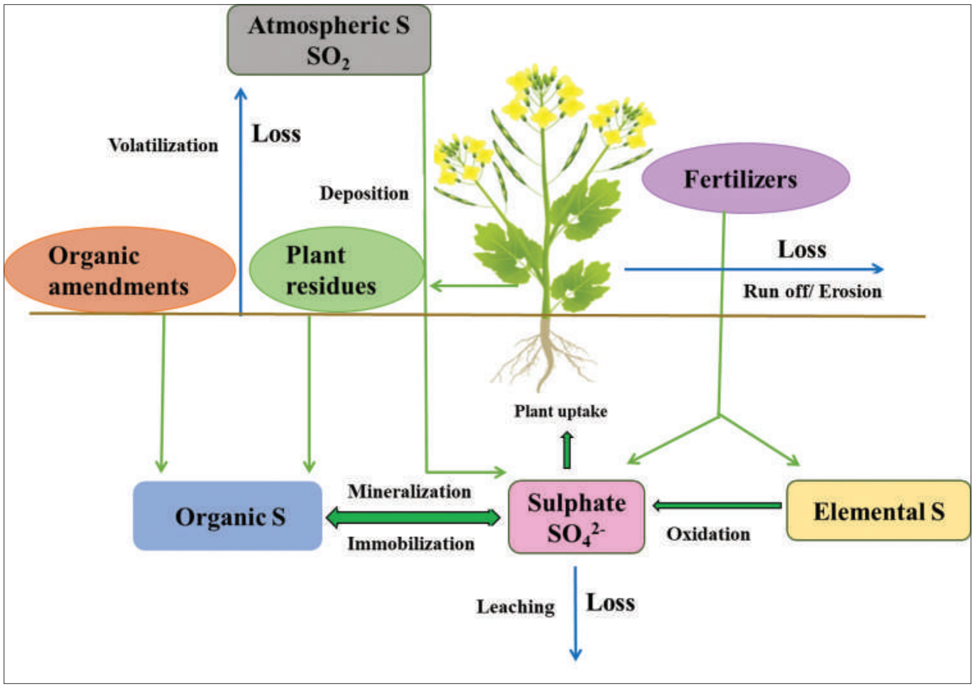

Figure 6: Transformation of S in agricultural soil

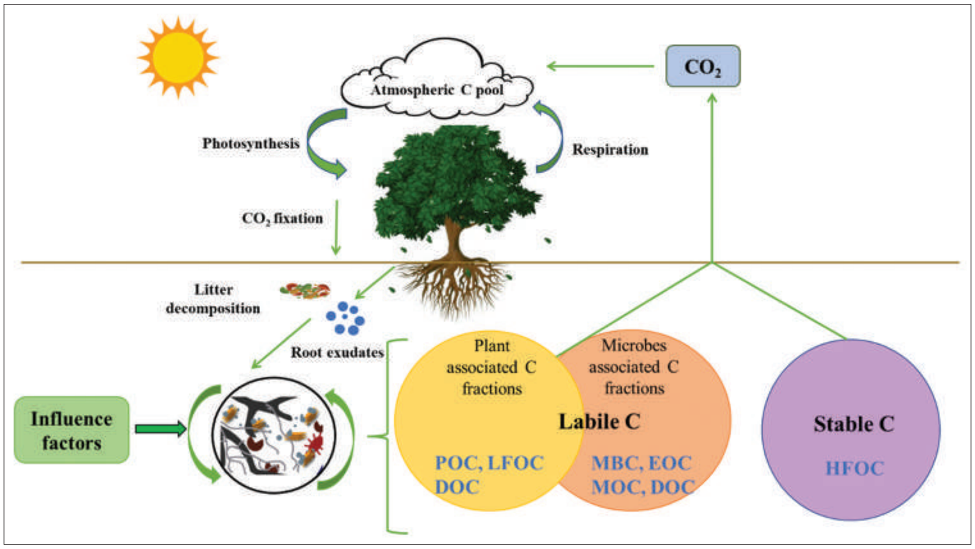

Figure 7: Organic carbon fractions influencing carbon cycle in soil

macroaggregates. These aggregates offer physical protection from microbial breakdown and enhance chemical resistance to decomposition. Changing soil physical and chemical properties to enhance these protective mechanisms can increase SOC storage, as long as carbon inputs stay the same. However, converting natural ecosystems into agricultural systems results in considerable losses of SOC. Studies showed that approximately 136 Pg of soil carbon has been lost since 1750 due to land-use changes (Lal, 2004). Davidson and Ackerman (1993) estimated that cultivation results in an average SOC loss of about 40% in the plough layer (0-30 cm). This decline in SOC negatively impacts soil fertility, C sequestration, and overall environmental sustainability. The primary driver of soil C loss in agroecosystems is intensive cultivation, with a new equilibrium in soil C taking decades to establish following land conversion (Luo *et al.*, 2010). The labile SOC fraction, which decomposes rapidly, contributes to ecosystem productivity, with approximately 70% of labile C from plant residues released as CO_2, while the remaining portion undergoes humification, forming stable carbon compounds that persist in soil for decades to centuries (Enchilik *et al.*, 2023). Increasing stable SOC through carbon sequestration strategies can mitigate climate change impacts and improve soil resilience against degradation.

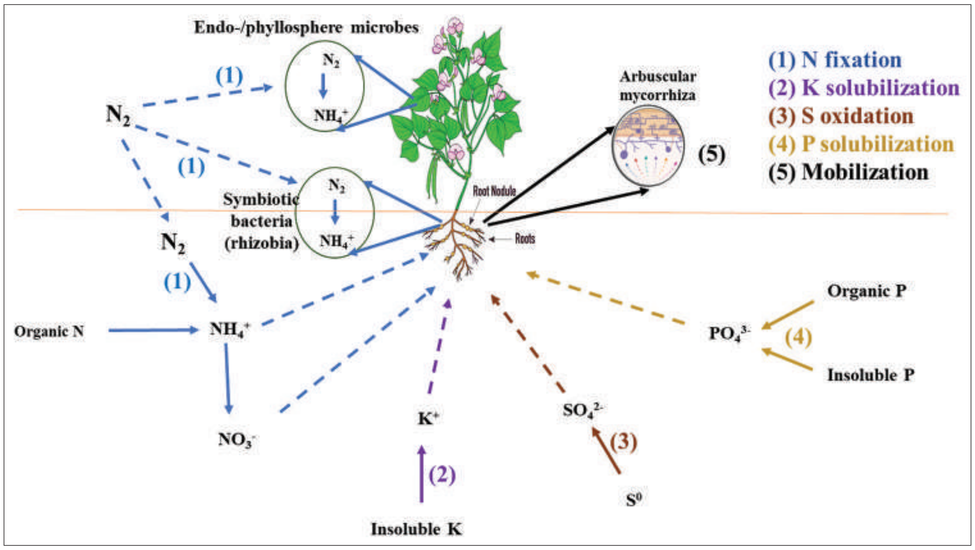

Figure 8: Important nutrient acquisition/transformation pathways mediated by microbes. Full arrows indicate microbial transformations, while dashed arrows indicate nutrient mobilization or movement (Mitter et al., 2021)

Table 2: A list of bacteria and fungi that help in nutrient availability

Nutrient	Solubilizing Bacteria	Solubilizing Fungi
N	*Rhizobium* spp. (symbiotic) (Miransari & Smith, 2007) *Azospirillum* spp., *Azotobacter* spp., *Acetobacter diazotrophicus, Azoarcus* spp., cyanobacteria, *Bacillus* spp., *Enterobacter* spp., *Xanthobacter* spp., *Gluconacetobacter diazotrophicus, Achromobacter* spp., *Arthrobacter* spp., *Azomonas* spp., *Clostridium* spp., *Beijerinckia* spp., *Corynebacterium* spp., *Rhodospirillum* spp., *Klebsiella* spp., *Derxia* spp., *Herbaspirillium* spp., *Pseudomonas* spp., *Rhodopseudomonas* spp. (Saharan & Nehra, 2011)	Arbuscular Mycorrhizal (AM) fungi (Podile & Kishore, 2006)
P	*Pseudomons, Bacillus* and *Klebsiella* spp., *Azorhizobium caulinodans, Rhizobium leguminosarum, Herbaspirillium seropedicae, Enterobacter, Arthrobacter, Micrococcus, Erwinia, Serratia, Rahnella, Synechococcus* spp. (Dash & Dangar, 2017)	*Penicillium, Mortierella* spp., *Fusarium, Trichoderma* spp., *Aspergillus, Paecilomyces* (Dash & Dangar, 2017)
K	*Paenibacillus mucilaginosus* (Hu *et al.*, 2006) *Bacillus circulans* (Zeng *et al.*, 2012) *Bacillus mucilaginosus* (Li *et al.*, 2007)	*A. niger, A. Terreus* (Prajapati *et al.*, 2012), *T. globose* (Rosa-Magri *et al.*, 2012)
S	*Thiobacillus* spp. (Miransari & Smith, 2007) *Thiobacillus, Thiothrix, Chlorobiaceae, Beggiato, Chromatiaceae, Ectothiorhodospiraceae* (Meyer *et al.*, 2007) *Thiobacillus dentirificans* (Beller *et al.*, 2006)	*Absidia, Alternaria, Acremonium, Aspergillus, Amanita, Aureobasidium, Epicoccum, Cephalosporium, Fusarium, Hymenoscyphus, Mortierela, Monilia, Mucor, Myceliophthora, Penicillium, Pisolithus, Phanerochaete, Rhodotorulla, Suillus, Rhizopogon, Trichoderma* (Czaban & Kobus, 2000)

MICROBES INVOLVED IN SOIL NUTRIENT AVAILABILITY

The soil ecosystem is the primary niche of microbes exhibiting about 10^8 to 10^9 taxa g^{-1} of soil (Huang *et al.*, 2014). Numerous studies have been done on the benefits of plant symbiosis with arbuscular mycorrhizal fungi (AMF) and *Rhizobium* for nutrient uptake (Dellagi *et al.*, 2020). Additionally, rhizospheric and endophytic beneficial fungi and bacteria can help plants develop their root systems and increase the bioavailability of insoluble nutrients (Figure 8, Table 2), which increases the host root's ability to explore for minerals and water (Tao *et al.*, 2019). AM fungi can enhance nutrient uptake by host plants through their extensive hyphal network, but more research is needed to fully understand their impact on nutrient uptake and compound production (Miransari, 2013). Soil microbes drive N cycling through biological fixation (*Rhizobium*, *Azotobacter*), ammonification (*Bacillus*), and nitrification (*Nitrosomonas*), converting N into plant-available NH_4^- and NO_3^-. Denitrifiers (*Pseudomonas*) may reduce N under low oxygen. PGPR (*Pseudomonas*, *Bacillus*) enhance plant N uptake, optimizing soil fertility sustainably. Soil contains organic and mineral P, with organic P having more availability due to microbial activities. Microbes can produce enzymes (phosphatases) (at smaller amounts compared with plants) and organic products such as organic acids (carboxylic acids), protons, etc., which can increase P availability in the soil by affecting the mineral P sources such as rock phosphate (Miransari, 2013). Numerous saprophytic bacteria (*Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans*, *Acidothiobacillus ferrooxidans*, *Paenibacillus spp.*) and fungi (*Aspergillus spp. and Aspergillus terreus*) (Haro & Benito, 2019) employ various mechanisms such as acidolysis, chelation, oxidoreduction, and the production of compounds like oxalate, lactate, gluconate, citrate, catechol, and pseudobactin to release

K from minerals (Uroz *et al.*, 2009). Like other nutrients, sulfur (S) undergoes biological transformations in the soil, carried out by soil bacteria such as *Thiobacillus sp.* Due to the hydrogen produced by these bacteria, S can be oxidized to sulphate and pH of soil can be reduced. Fungi (*Alternaria tenius*, *Aureobasidium pullulans*, *Epicoccum nigrum*, a range of *Penicillium* species, *Scolecobasidium constrictum*, *Myrothecium cinctum and Aspergillus*) (Vidyalakshmi *et al.*, 2009) are capable of oxidizing elemental S and thiosulphate. The transformation, primarily mediated by microorganisms, of organic S to inorganic sulphate (mineralization) and vice versa (immobilization) is crucial for S cycling in soils (Kertesz & Mirleau, 2004). Microbial activity, influenced by factors like temperature, moisture, pH, and substrate availability, plays a significant role in these processes (Sparling & Searle, 1993). Overall, soil microbes are indispensable for nutrient cycling, enhancing plant growth and soil fertility through diverse biochemical mechanisms.

TRENDS IN NUTRIENT CONCENTRATIONS ACROSS VARIOUS SOILS

Saline soil

Saline soils exhibit distinct trends in N, P, K, S, and C concentrations due to their unique physicochemical and biological constraints. N availability is severely limited in these soils primarily due to enhanced ammonia (NH_3) volatilization and suppressed nitrification processes (Li *et al.*, 2017, 2020). Studies report that soil salinity and sodicity strongly influence the rate of NH_3 volatilization, where up to 15 times higher NH_3 emissions were measured compared to the normal soil (Maqsood *et al.*, 2016). The high sodium (Na^-) content in saline soils disrupts microbial activity, further reducing N mineralization and organic N decomposition (Wong *et al.*, 2010). P dynamics are highly variable and salt-specific. Coastal saline soils typically require 16-32 ppm of available P for agricultural productivity (Bhadha *et al.*, 2012). P adsorption in saline soil can vary according to the type of salt. Interestingly, subsurface layers often exhibit higher P concentrations (21.3-24.1 ppm) than surface soils, due to higher pH value in the lower soil depth (5-10 cm) and lower P fixation (Khanam *et al.*, 2020). K availability follows a similar depth-dependent trend, with subsurface layers containing 17.85% more K due to sedimentation, flooding, and weathering processes that redistribute K from upper to lower soil horizons (Khanam *et al.*, 2020). However, excessive Na^+ in saline soils can displace exchangeable K^+, which makes leaching loss of K and deficiency symptoms can be shown in crops (Rengasamy, 2010; Haque, 2018). Besides, S contents are also lower in saline soils because of less chemical weathering controlled by lithology, runoff, temperature, physical erosion, morphology, soil, ecosystems, land use, and tectonic activity (Hartmann & Moosdorf, 2011). SOC is also significantly reduced (1.0-1.5%) in saline soils due to reduced plant biomass input and reduced microbial decomposition (Wong *et al.*, 2010; Sarkar *et al.*, 2019). The combined effect of low SOC, high salinity, and poor nutrient retention capacity exacerbates nutrient leaching and ultimately makes soil infertile. For this, Farmers abandon their land in saline areas (Islam *et al.*, 2023). Additionally, micronutrient imbalances are also common in saline soils due to high pH and salt-induced precipitation, further exacerbating fertility challenges (Rengasamy, 2010). The interplay of these factors underscores the complexity of nutrient dynamics, necessitating tailored management strategies to improve productivity in saline soils.

Acid soil

Soil reaction affects the chemical forms of nutrients, and some nutrients undergo reduction and oxidation reactions, which affect their solubility and availability. Soil acidity influences different biogeochemical processes in soil carbon cycling, particularly SOM decomposition (Curtin *et al.*, 1998). Lower soil pH significantly depresses microbial activities during organic matter decomposition. Soil acidification facilitates chemical and physical protection of SOM by solid phases and increases the positive charge on mineral surfaces, thus enhancing the adsorption of organic matter (McBride, 1994). Acidification also reduces the ionization of organic acid, which weakens the repulsion between negatively charged clays and organic matter in aggregates (Sparks, 2003). This protection is needed to conserve organic matter content (Zhang *et al.*, 2020). More SOM means More SOC present in acid soil. Total N values are low when organic matter content is low. Low pH in acid soils slows nitrification. In these conditions, NH_4-N oxidizes faster than NO_2-N, causing the accumulation of nitrites in soil (Smith *et al.*, 1997). Nitrites in acidic soils, even in small quantities, can be toxic to plants and microorganisms. High levels of ammonium N and aluminum in acid soils can significantly reduce nitrification activity (Kresović *et al.*, 2010). The availability of P in acidic soils is also affected. Maintaining P distribution is important in acidic soil (Shah *et al.*, 2019). The mineralization of organic P to inorganic forms is enhanced by optimal soil pH, proper nutrient levels and favorable soil physical properties. Inorganic P in soil binds with Fe and Al compounds, and its availability depends on the slow dissolution of these minerals. In acidic soils, more Fe and Al form insoluble phosphate compounds, reducing P availability (Islam *et al.*, 2014). Low SOM and rapid decomposition at high temperatures further deplete soil P reserves. Acid soil also shows poor K retention capacity. In a study by Kassa *et al.* (2021), water-extractable K (H_2O-K) concentrations ranged from 0.13 to 0.34 $cmol_c\ kg^{-1}$ soils in acid soils. The mean concentrations of NH_4OAC-K and HNO_3-K were 0.25 $cmol_c\ kg^{-1}$ soils, and mean values for nonexchangeable-K and exchangeable-K concentrations were 0.11 and 0.14 $cmol_c\ kg^{-1}$ in soils, respectively, across different land use types (Kassa *et al.*, 2021). Acid soils have low S fractions due to unfavorable soil conditions and slow organic S mineralization. Low pH negatively affects the availability and transformation of S in these soils (Athokpam *et al.*, 2007). Sulphate is a product of pyrite oxidation and may form Fe/Al hydroxyl sulphate minerals to prevent the occurrence of extreme acidification in soils (Huang *et al.*, 2016). Organic amendments and chemical fertilizers increase S fractionation in acid soil, while no application of S decreases fractionation (Dutta *et al.*, 2013). S amounts decreased due to continuous cropping and reduced sowing depth, while combining 100% N, P, and K with manure showed positive results in acid Alfisols (Gourav *et al.*, 2018). Overall, managing soil acidity is important to improve nutrient availability and maintain soil fertility. Proper soil management practices, including the use of lime, organic matter, and balanced fertilizers, can help reduce the negative effects of low pH and support better crop growth in acid soils.

Calcareous soil

In calcareous soil, different fractions of SOC, including DOC, MOC, and recalcitrant organic carbon (ROC), significantly decrease (Yang *et al.*, 2021). In an experiment by Williams *et al.* (1960), it was found that organic C content was approximately 40% lower in calcareous soil. N dynamics in calcareous soils are strongly influenced by high pH, which helps in rapid urea hydrolysis and significant ammonia volatilization (up to 60% of applied N). High pH also accelerates nitrification, which results in potential nitrate leaching (Maqsood *et al.*, 2016). Additionally, calcium carbonate ($CaCO_3$) can immobilize N by enhancing microbial demand during organic matter decomposition, further reducing plant-available N. Calcareous soils exhibited lower organic P content than the non-calcareous soils. Organic P comprises around 40% of the total P in calcareous soils (Williams *et al.*, 1960). Compared with other nutrients, P is the least mobile and least available for plants in soil, especially in calcareous soil (Song *et al.*, 2017). Soil chemical factors, specifically exchangeable Mn and Zn, CEC, and carbonate, play a crucial role in controlling P levels in calcareous soils (Bouray *et al.*, 2024). The excessive application of P fertilizer, particularly OM, led to a significant accumulation of Pi and increased the risk of pollution from organic farming (Song *et al.*, 2017). The concentration of K in calcareous soil for plant uptake is limited by its fixation and variations in basic cation ratios. The issue of K availability and uptake by plants in calcareous soils is primarily due to antagonistic relationships with other basic cations like Na^+, Ca^{2+}, and Mg^{2+} (Memon *et al.*, 2024). Although K is usually plentiful in calcareous soils, much of it remains unavailable to plants because of imbalances between the levels of Ca^{2+}, Mg^{2+}, and K^+. These may result in K deficit through competitive uptake interactions (Weil & Brady, 2017). The total S content is significantly higher in the calcareous soils due to water-insoluble sulfate, which is closely associated with the $CaCO_3$ content (Williams *et al.*, 1960). In calcareous soils, about 93% of SO_4^{2-} is fixed in co-precipitation with $CaCO_3$ (Germida *et al.*, 2021). Therefore, managing nutrient availability in calcareous soils requires careful attention to pH effects, nutrient interactions, and proper fertilizer application. These things can reduce nutrient losses and improve nutrient uptake by crops.

METHODS FOR NUTRIENT FRACTION DETERMINATION

Understanding nutrient fractions in soil is essential for evaluating soil fertility, nutrient cycling, and ecosystem productivity. Scientists use different laboratory methods to measure various forms of nutrients in soils. These methods help distinguish between total, available, and different chemical-bound fractions of nutrients. The choice of method depends on the specific fraction being analyzed and the soil's physicochemical properties. An overview of commonly used methods for determining various nutrient fractions in soil is given in Table 3.

EFFECTS OF LAND USE AND MANAGEMENT ON NUTRIENT FRACTIONS

Land use and management practices significantly influence soil nutrient fractions with both short-term and long-term agricultural, forestry, and urban development activities. In the short term, agricultural practices such as tillage, fertilization regimes, and crop rotations can quickly change the availability and distribution of nutrient. Intensive farming, characterized by frequent tillage and synthetic fertilizer application, intensifies inorganic nutrient fractions (e.g., nitrate, ammonium, and soluble P) due to accelerated mineralization and direct nutrient inputs (Jaiyeoba, 2003; Beheshti *et al.*, 2012). No-tillage systems exhibit superior SOC retention. In the top 10 cm of soil (surface soil), TOC levels reach 37.0 g kg–¹, while deeper layers (subsurface soil:10-20 cm) hold 31.4–31.6 g kg⁻¹ (Liu *et al.*, 2016; Topa *et al.*, 2021). These systems also enhance SOM, total P, and K content compared to conventional tillage (Bolliger *et al.*, 2006; Redel *et al.*, 2007; Zamuner *et al.*, 2008; Haque *et al.*, 2025).

Management practices have a significant impact on N-dynamics. Leguminous cover crops enhance N availability through biological fixation (Kapkiyai *et al.*, 1999). But, naturally fertile soils such as Chernozems and peatlands maintain elevated N stocks (Gworek *et al.*, 2021). However, intensive tillage reduces both SOC and N stocks in the topsoil (Beheshti *et al.*, 2012), with long-term cultivation speeding up the decomposition of organic matter (Kapkiyai *et al.*, 1999). Horticultural systems, particularly guava orchards, exhibit higher organic N fractions (9.72 g kg⁻¹ TOC) when compared to sugarcane monocultures (Kaushik *et al.*, 2018). P availability is strongly influenced by tillage methods. Autumn ploughing with straw retention increases various P fractions ($NaHCO_3$-Pi, NaOH-Po, HCl diluted Pi) compared to conventional tillage (Ahmed *et al.*, 2020). Total and readily available P are increased through long-term integrated nutrient management that combines organic manure with inorganic fertilizers (Vats *et al.*, 2001; Haque *et al.*, 2015). K distribution varies by land use. For example, banana cultivation favors exchangeable and non-exchangeable K forms (Hoque *et al.*, 2020). Conservation Agriculture (CA) practices have a particularly strong effect on S dynamics. Minimal soil disturbance combined with high residue retention increases total S (584-668 mg kg⁻¹), organic S (50-153 mg kg⁻¹) and water-soluble S (6-17 mg kg⁻¹) through enhanced SOC sequestration (Kumar *et al.*, 2022). Conversely, continuous cropping without S supplementation depletes soil S reserves (Scherer *et al.*, 2012). Microbial communities play a crucial role in nutrient cycling, with grasslands and forests having higher MBC and MBN compared to arable lands (Liu *et al.*, 2016). Rice-based systems with organic amendments maintain higher N, P, and K levels (Hoque *et al.*, 2020), while horticultural systems show superior C retention (238.14 mg kg⁻¹ MBC) and nutrient cycling (Kaushik *et al.*,

Table 3: A list of methods for Nutrient Fraction Determination

Nutrients	Fraction	Method of determination	References
N	Total N	Kjeldahl method	Bremner & Mulvaney, 1982
	Dissolved N	0.5 M K_2SO_4 extractor and determination using a TOC-VCPH+TNM-1 organic carbon analyser	Sun *et al.*, 2021
	Ammonium N	Steam distillation method	Bremner & Keeney, 1965
	Colorimetrically in 1 M KCl extractor (1:5 w/v) using a San++continuous flow analyser	Sun *et al.*, 2021	
	Nitrate and Nitrite	Steam distillation method	Bremner & Keeney, 1965
	Colorimetrically in 1 M KCl extractor (1:5 w/v) using a San++continuous flow analyser	Sun *et al.*, 2021	
	Microbial biomass N (MBN)	Chloroform fumigation–K_2SO_4 extraction methods	Sun *et al.*, 2021
P	Organic P	0.5 M HCl Extraction method	Williams *et al.*, 1976
	1 M HCl+calcination Extraction method	Burrus *et al.*, 1990	
	Available p	Olsen method	Olsen *et al.*, 1954
	Labile P	1 M NH_4Cl Extraction method	Chang & Jackson, 1957; Hieltjes & Lijklema, 1980
	Occluded P		
	Al-bound P	0.5 M NH_4F (pH 8.2) Extraction method	Chang & Jackson, 1957
	Fe-bound P	0.1 M NaOH Extraction method	Chang & Jackson, 1957
	Ca-bound P	0.5 M HCl Extraction method	Chang & Jackson, 1957; Hieltjes & Lijklema, 1980
	Microbial P	Chloroform/Bicarbonate Technique	Hedley *et al.*, 1982
K	Total K	$HF\text{-}HClO_4$ digests	Black, 1965
	Mixture of HCl and HNO3, 'aqua regia'	Fotyma, 2007	
	Water soluble K	Shaking soil-water mix (1:2) for 2 hours, standing it for 16 hours, filtering, analyzing with flame photometry (water extraction method)	Sparks, 1980
	Exchangeable K	Ammonium acetate and sulphuric acid extraction method	Sparks, 1980; Fotyma, 2007
	Non-exchangeable K	Hot HNO_3 extraction method	Sparks, 1980
	Mineral K	Selective dissolution using Na-pyrosulfate fusion	Sparks, 1980
S	Total S	Sodium hypobromite digestion method	Tabatabai & Bremner, 1970
	Sulphate S	Hydriodic acid reagent reduction	Johnson & Nishita, 1952
	Elemental S	Chloroform extraction, fuming HNO_3, KNO_3 digestion and determination (ICP-AES)	Zhao *et al.*, 1996
	Organic S	Wet (acid) and dry-ash (alkaline) oxidation methods to convert into sulfate	Rossete *et al.*, 2008
C	POC	Sodium hexametaphosphate as a dispersing agent	Chan, 2006
	LFOC	Modified (Strickland and Sollins, 1987) method	Janzen *et al.*, 1992
	EOC	0.333 M $KMnO_4$ oxidation method	Blair *et al.*, 1995; Wang *et al.*, 2020
	DOC	DOC fractionation method	Leenheer & Huffman, 1979
	MBC	fumigation–extraction method	Yang *et al.*, 2009
	TOC	standard Walkey Blac k rap id titration method Standard Walkey Black rapid titration method	Walkley, 1947
	HFOC	Dry combustion method (900°C) using a CN analyzer	Tan *et al.*, 2007

2018). These findings underscore the importance of sustainable practices - reduced tillage, organic amendments, and better fertilization approaches for maintaining soil health and proper nutrient balance in soil.

SOIL MANAGEMENT PRACTICES FOR NUTRIENT BALANCE

Nutrient fractions in soil are low due to factors such as erosion, leaching, intensive farming, and poor soil management practices. Without conservation tillage, crop residue retention, or organic amendments, SOM decreases, microbial activity declines, and nutrients are lost. Additionally, unsustainable land use changes and lack of crop rotation further deplete soil fertility, reducing nutrient availability for plants. Managing the land properly can help conserve soil, prevent erosion, and maintain soil fertility, ensuring sustainable agricultural productivity. Soil nutrient contents are expected to be recoverable in agricultural systems by conservation tillage, land use changes, and the use of efficient and controlled agricultural practices, such as irrigation and the use of fertilizer and pesticides (Reijneveld *et al.*, 2009).

Conservation Tillage

Conservation tillage management directly impacts SOC, MBC, available N, potential N mineralization, total N, and extractable P levels in agricultural soils by promoting C stabilization and minimizing decomposition (Shokati & Ahangar, 2014). Intensive and conventional tillage caused a decline in soil fertility, decreased water holding capacity of soil, and weakened soil structure, making it more vulnerable to erosion by water and wind. Farmers continue to use higher fertilizer rates to maintain high crop productivity (Du Preez *et al.*, 2001). Conservation tillage enhances long-term N availability to plants by increasing soil N retention and the labile N pool in upper soil layers (Rice *et al.*, 1986; McCarty *et al.*, 1995). The vertical stratification of plant nutrients occurs in the soil profile as a result of conservation tillage, particularly no-tillage (Bauer *et al.*, 2002). Soil samples under conservation tillage showed a notable stratification of p and K. Doran (1987) reported that microbial biomass and potentially mineralizable N in the 0-7.5 cm surface layer of no-till soils were 34% higher than those of ploughed soils. Minimum tillage increases the activities of arylsulfatase and rhodanese enzymes, both of which are involved in S cycling in soils (Deng & Tabatabai, 1997). The activities of these enzymes regulate the availability of both organic and inorganic S to plants and microbes. In an experiment by Lakhena *et al.* (2025), it was found that, conservation tillage (Zero Tillage) increased maize grain equivalent yields by 24.4-25.2%, enhanced microbial biomass-C and -P by 7.65-11% and 23.2-31.9%, respectively, and improved water productivity by 11.9-12.9% compared to conventional tillage. It significantly improves topsoil chemical properties, increasing organic matter, organic C, Total C, total and available N, P, K, Ca^{2-}, Mg^{2-}, and CEC, with no-till with straw (NTS) boosting OM, OC, and TC by 14%, 5%, and 37%, respectively, compared to no-till without straw (Lv *et al.*, 2023).

Crop Residue Retention

Burning crop residues is a serious issue worldwide because it causes the loss of large portions of N, P, and C present in the plant residue. It also accelerates the losses of organic matter, increases CO_2 emissions, and reduces soil microbial activity (Biederbeck *et al.*, 1980). Crop residue retention at soil surface conserves soil and water for sustaining crop production (Zhao *et al.*, 2019). It enhances SOC, which in turn improves soil structure, CEC, water-holding capacity, and reduces bulk density, all contributing to better nutrient availability. As a carbon-rich biomass, crop residues contain carbon (40%-45%), N (0.6%-1%), P (0.45%-2%), K (14%-23%), and microelements, which are necessary for crop growth (Wang *et al.*, 2023). Zhao *et al.* (2019) observed that straw and partial fertilizers incorporation significantly increased the soil available N at soil depths of 0-20 cm by an average of 64%. Murphy *et al.* (2016) found that crop residue retention increased fertilizer N recovery by 41% in the soil-crop system. Overall, residue retention provides farmers with effective options to enhance soil function and minimize nutrient losses, especially in sandy soils of sub-humid tropical areas.

Crop Rotation

Long-term implementation of more diverse and extended crop rotations contributed to soil quality by improving soil aggregation, increasing porosity, increasing pH, and accruing SOM, N, and microbial biomass (Wu *et al.*, 2025). These improvements collectively improve water availability to plants, promote better movement of water through the soil, and support higher crop yields. Complex crop rotations, including alfalfa as a legume phase, improve soil quality more than simple rotations (Kiani *et al.*, 2017). Perennial legumes have deep tap roots lifting soil for better tilth and water-holding capacity (Danga *et al.*, 2009). Kiani *et al.* (2017) reported that, in long rotations, microbial biomass was 1.3 times higher than in simple rotations. Diverse and extended crop rotations improve the quality and quantity of the plant residues available for microbial communities (Tiemann *et al.*, 2015). The positive effects of crop rotations on yield and soil quality tend to increase over time. Including legume crops in rotation provides a sustainable approach to agriculture, helping to enhance food security and improve soil health by supporting a balanced nutrient supply.

Biochar Application

Biochar is gaining popularity for its ability to sequester carbon, enhance soil health, increase the surface area of soil, increase fertility, and improve crop productivity and quality (Alkharabsheh *et al.*, 2021). According to research by Nelson *et al.* (2011), biochar is a solid byproduct of the thermochemical production of bioenergy, and it increases nutrient availability in soils by increasing cation retention and reducing phosphate adsorption. Biochar made from nutrient-rich feedstocks contains relatively high levels of nutrients that are more readily available to plants. In general, biochar amendment improves soil fertility, yet the effect is more apparent for poor soils (e.g., acidic, highly leached) than for originally fertile soils (Igalavithana *et al.*, 2016). Biochar application in the soil can affect soil microbial community structure due to its high sorption capacity (Lehmann *et al.*, 2006), change the soil pH, as well as modify of microbial environment. Biochar application increased soil pH by 0.5 units and available phosphorus by 20% (Joseph *et al.*, 2021). It also improved soil aggregate stability by 50%, plant available water by 20%, and poplar tree growth by 20%, depending on the dose (Antonangelo *et al.*, 2025). N-enriched biochar fertilizer (51% biochar with 10% N) reduced greenhouse gas emissions by 14% compared to urea treatment (Sharma *et al.*, 2025). To enhance soil quality and boost crop yields without harming the environment, biochar can be a valuable amendment when applied in appropriate, balanced amounts.

Green Manuring

Green manuring enhances the physical, chemical, and biological properties of soil, which in turn leads to improved crop yields. The ability to deliver nutrients depends on the composition of the amendments, but green manure amendments stimulate soil microbial growth and activity, which leads to the mineralization of plant nutrients (Randhawa *et al.*, 2005). Green manures made from legumes are a crucial source of N for organic crop production. According to estimates, a green manure crop that is 40-50 days old can produce up to 80-100 kg N/ha (Dubey *et al.*, 2015). It can replace 50-60 kg of fertilizer N per ha, even if only half of this N is usable by crops (Sharma *et al.*, 2017). It can also effectively increase the organic carbon pool in the soil (Hu *et al.*, 2022). Increasing the amount of biomass in soil through green manures is known to increase the accumulation of organic carbon in soil (Nandan *et al.*, 2019). Green manuring improves P availability in rice by converting residual and unavailable native and fertilizer P to plant-available form (Chimouriya *et al.*, 2018). The improvement in soil nutrients by applying green manure is mainly due to two factors: nutrients released from decomposing green manure and the increase in organic matter, which improves soil structure and nutrient retention (Wei *et al.*, 2025). Green manure adds nutrients and boosts nutrient mineralization by raising soil organic matter. Understanding this can offer valuable insights for optimizing green manure practices to sustainably improve soil fertility.

Land Use Changes

Land use changes significantly affect soil fertility, increase erosion and compaction, and modify the physical, chemical, and biological properties of the soil (Geissen *et al.*, 2009; Moges *et al.*, 2013). It also impacts nutrient and carbon fluxes in soils and vegetation, biomass production, and human land management decisions (Priess *et al.*, 2001). Hydrological processes are impacted by changes in land use. For instance, afforestation increases interception, and transpiration has an impact on nutrient transport and erosion. Also, highly effective soil cover can lessen erosion and surface runoff (Calder, 1993). Land conversion, such as changing natural vegetation to farmland or grassland to cropland, can greatly affect soil chemical properties, including soil carbon levels and nutrient concentrations. For example, Lumbanraja *et al.* (1998) found a decrease of N, P, and organic carbon in surface soil layers after conversion of primary forest to coffee (*Coffea arabica* L.) plantations and cultivated lands in the period 1970-1990. In New Zealand, the conversion of native forests to permanently grazed pasture led to increased soil carbon content due to greater soil fertility and denser root systems (Sparling & Schipper, 2004). The residence time of soil C decreases as OM decomposition accelerates due to increased energy and nutrient availability (Sanderman *et al.*, 2016). In another study, it was found that the conversion of natural forests to grasslands resulted in considerable losses of SOC and TN stocks, which can be linked to the disturbance of natural forests (Fartyal *et al.*, 2015). Therefore, when planning land-use changes, it is essential to consider their impact on soil nutrients. In fact, converting land from natural vegetation often leads to soil quality decline. As a result, policies should encourage practices that promote the buildup of soil organic matter and the restoration of both macro- and micronutrients. To restore soil health, integrated approaches are recommended, like precision fertilizer blends with micronutrient addition, adoption of soil conservation techniques, and strategic fallow periods to allow natural regeneration, etc.

RESEARCH GAP AND FUTURE DIRECTIONS

This review has synthesized the current state of knowledge, yet several critical areas of that research remain underexplored. Closing these gaps is essential for advancing sustainable soil management. While nutrients like C, N, P, S, and K are often studied in isolation, there is a lack of comprehensive understanding of their interconnected cycling and stoichiometric relationships in soil. The transformation of one nutrient directly influences the availability of others. Future work must adopt a multi-nutrient approach to unravel these complex interactions. The microbial drivers of nutrient cycling remain poorly identified. In the future, researchers must use molecular tools to pinpoint the exact microbes that mobilize fixed P and K, mineralize organic S, and stabilize C, and which gene is responsible for which nutrients' mobilization or availability. This directly links the microbes to nutrient turnover in the field (Jansson & Hofmockel, 2018). Long-term effects of management practices like biochar application or conservation agriculture on nutrient pools are not fully quantified. It is still unclear how much these amendments help to mobilize or store different fractions of various nutrients. Furthermore, research must better integrate how climate change factors will interact with these management strategies to alter nutrient cycling and availability in the future. Besides, there is a translational gap between research and practice. Future efforts should focus on developing standardized fractionation methods for understudied nutrients and on incorporating this data into predictive models. The ultimate goal is to create practical decision-support tools that help farmers apply the right nutrient, in the right form, at the right time. Addressing these priorities will move the science from describing nutrient pools towards predicting and managing soil fertility for long-term resilience and productivity.

CONCLUSION

Climate change and improper management practices have threatened the sustainability of soil of the world nutrient supply. The distribution and forms of different nutrients accumulated in soils and their availability to plants have paramount importance in balanced fertilizer application for sustainable agricultural practices in recent years. The mineralization of organic nutrients is a key source of nutrients for crop growth. The forms in which nutrients exist and their relationship with soil properties determine the soil's ability to supply nutrients by controlling their release and movement. Estimating the status and distribution of nutrient fractions and their relationship with soil physical and chemical properties are important to develop efficient nutrient management strategies, especially in nutrient-deficient areas under different land use practices. There is limited information about the different nutrient pools present in various soil types. Researchers worldwide need to pay more attention to studying the amount and distribution of nutrient fractions across different soils and cropping systems. Future research should examine a multi-nutrient approach to unravel these complex interactions and move towards predictive soil fertility management. Understanding how nutrients move and cycle in these systems is essential for managing soil fertility effectively. This study offers important information on how diverse cropping systems affect nutrient fractions in the soil. Gaining this knowledge can help develop better soil management approaches and support more sustainable farming practices.

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