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Factors Influencing the Activities of Soil Enzymes Involved in Nutrient Cycling in Terrestrial Ecosystems

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Abstract
Soil ecosystems are important in sustaining flora, fauna, and microbes. It provides key nutrients to the soil—microbial metabolism to help in agricultural production, habitat maintenance, biodiversity restoration, and environmental balance. Soil enzymes play an important role in nutrient cycling, mainly carbon, nitrogen, and phosphorus, hence helping to create the availability of nutrients through degradation of substrate and exchange of energy. Microorganisms play a special role in enzyme production, both intracellularly and extracellularly. They are involved in microbial biomass production, organic matter decomposition, and soil productivity. Various soil parameters, viz., soil physicochemical activity, microbial activity, soil contamination, climatic factors, soil operational practices, and seasonal and land use conversion influence the soil enzyme activity. Enzymes play an important role in maintaining soil fertility and health. Therefore, soil enzymes are a great tool for evaluating the soil condition and ecosystem productivity.

Keywords: Soil Enzyme; Microorganism; Ecosystem; Soil Fertility; Nutrient Cycling

Introduction

India's semiarid tropical region is seeing a significant population increase, leading to deforestation, land conversion, and agricultural land expansion to meet the demand for food, promote economic growth, and alleviate deficiency. These affect the global climate system, soil properties, and ecosystem functioning. Semiarid areas have shown higher sensitivity to these changes due to variations in seasons and climate. This area is classified according to fluctuations in precipitation, high evaporation, and extremely hot winds with great velocity. Different temporal and geographical patterns in arid and semi-arid areas affect the soil composition, vegetation composition, degree, and length. These areas are spread over 6.5 million km² on Earth's surface, with a 15% portion and a habitat of 14.5% of the world's population (Walker, 2010). Furthermore, in India, 37% of the country is covered by a semi-arid portion with a spread of over 970,530 km². (Kalsi, 2007). Distribution of semi-arid zones in different states of the country, including Punjab, Haryana, Maharashtra, Rajasthan, Madhya Pradesh, Uttar Pradesh, Karnataka, Gujarat, Tamil Nadu, and some regions of Andhra Pradesh.

Due to different climatic conditions and composition of the soil microbiome, semi-arid areas had a diverse cropping system mainly including sorghum, mustard, soybean, groundnut, and pulses. In developing countries like India, which is prioritizing agricultural production, soil health provides the key input in production, yield, and combating environmental degradation. Soil fertility and status are maintained by the application of key nutrients such as nitrogen, phosphorus, potassium (NPK), sulfur (S) and carbon (C) which are also involved in nutrient cycling to circulate the substance in the plant-soil-microbial ecosystem to attain growth and production; decomposition of soil organic matter; and speeding up biological processes to energy transfer (Gianfreda, 2015). A healthy soil microbial population and their activity is responsible for increased enzyme activity.

Soil enzymes

Soil enzymes are mainly involved in soil organic matter decomposition, microbial biomass production, and degradation, which enhances soil fertility and quality by transforming organic matter to provide nutrient. Enzymes that produce and function inside the cells are regarded as intracellular, whereas extracellular enzymes are produced by cells and secreted outside the parent cell in the environment to functioning. They are synthesized by plants, animals, and microbes. Important enzymes, namely urease, phosphatase, and β-glucosidase, are crucial for the cycling of nitrogen, phosphorus, and carbon, respectively. They are considered as extracellular soil enzymes involved in energy transformation, environmental productivity, and ecosystem sustainability. However, dehydrogenase works as the oxidoreduction class of enzymes produced mainly by microbial cells categorized as intracellular soil enzymes, functioning effectively in supporting both plant and microbial growth (Burns et al., 2013). Numerous elements within the soil ecosystem affect the activity of enzymes, which aid in the biochemical activities that are responsible for enzyme functioning that convert substrates into products. These are highly sensitive to changes in soil community structure, composition, nutrient type, and availability. Therefore, the assessment of soil enzymes in natural and agroecosystems provides useful information about soil health and fertility. The determination of soil fertility by using a solo enzyme has been evidenced to be inappropriate due to specific enzymes catalyzing specific reactions responsible for reacting towards specific substrates, which cannot be revealed by the general soil microbial activity that is made up of a combination of different enzyme reactions (Nannipieri et al., 2012). Thus, the evaluation of a combination of enzymes provides valuable information about the factors controlling plant litter degradation and soil nutrient cycling. The anthropogenic alteration in abiotic and biotic components in the soil causes alteration in soil biochemical function and soil organic matter dynamics, consequently leading to soil enzyme production and functioning.

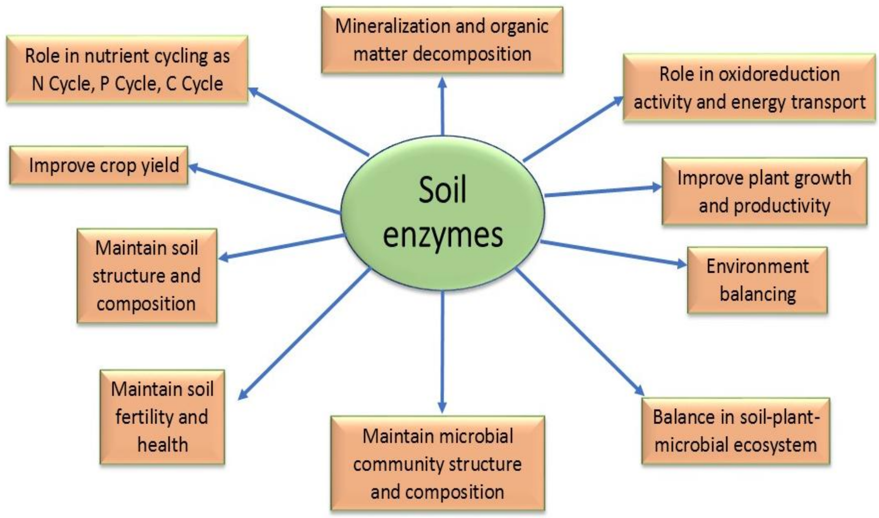

Figure 1. Role of soil enzymes in soil-plant-microbial ecosystem

Furthermore, it has been discovered that the biodegradation of resistant and xenobiotic substances is influenced by the soil's enzyme makeup. According to Acosta-Martínez and Waldrip (2014), hydrolases, including urease, alkaline phosphatase, and β-glucosidase, are essential markers of soil quality.

Factors affecting soil enzyme activity

Although previous studies have demonstrated a considerable association between soil enzymes and other soil parameters, the degree of this correlation varies greatly according to the types of enzymes and other environmental conditions. Interestingly, temperature and rainfall are considered two important factors influencing soil microbial populations and enzymatic activities in terrestrial ecosystems (Malik and Bouskill, 2022). Furthermore, variables such as pH, soil composition, and organic matter concentration vary geographically and seasonally, influencing the soil enzyme activity (Guox et al., 2012). There are many other factors, including climate change (Fanin et al., 2022), land use type (forests vs. cultivated fields) (Francioli et al., 2014), landscape position (Du et al., 2015), various tillage techniques (Smith et al., 2016), nutrient availability (Allison et al., 2011), soil depth (Xiao et al., 2018), natural soil properties (parent material and vegetation), fertilization techniques, or crop rotation plans (Gulser et al., 2016), are examples of best practices in soil management that also affect enzyme activity. Soil production and health can improve by comprehending these connections. Through the effects of osmotic potential and particular ions on enzymes, increased salinity in soil lowers enzyme activity and modifies microbial biomass (Rath and Rousk, 2015).

The effect of seasonal variation on the cycle of C, N, and P is shown by several tropical ecosystem processes, including fine root development (Cordeiro et al., 2020) and plant litter formation (Wu et al., 2016). Furthermore, although some research reported comparatively greater soil enzyme activity in colder conditions (Luo et al., 2020), other studies found enzyme activity showing its maximum potential in warmer periods of the season (Baldrian et al., 2013). As a result, the correlations could differ depending on the vegetation pattern and certain climatic zones. The operation of ecosystems depends on the soil enzyme activity, and pollutants such as heavy metals decrease their activities, particularly for arylsulfatase, dehydrogenase, and β-glucosidase. Higher clay content can counteract these effects by buffering against nutrient disruption (Aponte et al., 2020). The soil microbiome and the synthesis of its enzymes are impacted by varying land uses. Land use transformations' influence on soil microbial ecosystems and soil enzymes by influencing the soil organic matter composition and soil type and property has been the subject of several studies in India (Kumar and Ghosal, 2017; Meena and Rao, 2021). However, there is not much data regarding the comparison of microbial properties and enzymes in different land use/cover in different seasons in the Indian semi-arid region's soil.

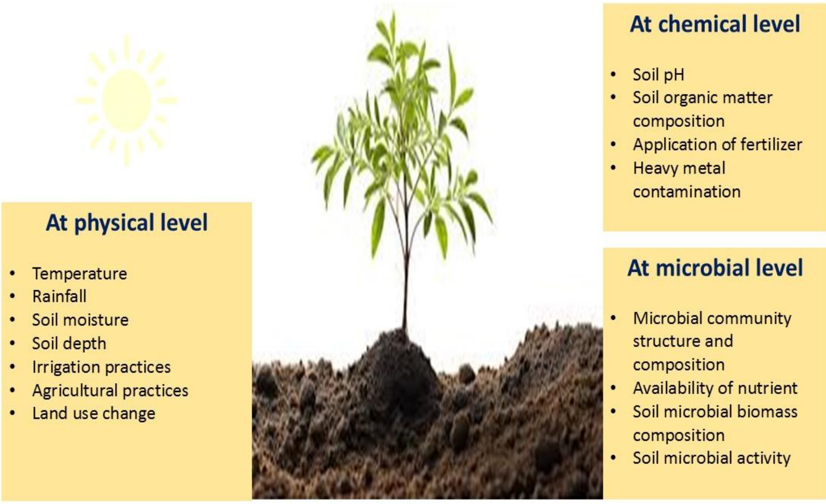

Figure 2. Factors affecting soil enzyme activity at physical, chemical, and microbial levels

Numerous studies conducted worldwide indicate that, in comparison to other land uses, the forest ecosystem exhibits the greatest levels of enzymatic activity (Xu et al., 2019; Barbosa et al., 2023). In the forest ecosystem and traditional farming to plantation, conversion improves the soil's water-holding capacity and organic carbon, which in turn increases enzyme activity and microbial biomass carbon (MBC) (Singson et al., 2019). Since tillage and other soil management practices have a significant influence on enzyme activity in agricultural and farmland settings (Barbosa et al., 2023). Fertilization treatments, particularly organic amendments, improve soil fertility and quality by increasing crop yields, microbial diversity, and enzyme activity. The significance of taking into account the natural spatiotemporal variability in enzyme activity when evaluating soil pollutants is highlighted by Lebrun et al. (2012). According to research conducted worldwide, afforestation dramatically raises enzyme activity due to increased soil carbon, nitrogen, and pH levels, especially in degraded tropical settings (Huang et al., 2022). Compost additions help offset these losses by increasing enzyme activity, but drought stress lowers enzyme production by changing microbial structure and abundance, which impacts soil fertility and plant productivity, according to earlier research on the effects of stress conditions on soil (Bogati et al., 2022). Lastly, edaphic elements such as pH and oxygen availability affect the enzyme activity in the dry soils of the South Mediterranean, which rise with soil depth. This highlights the relevance of environmental circumstances to enzyme dynamics (Ghiloufi et al., 2019).

Soil enzymes and their studies

Crop residue quality, moisture content, soil pH, and management techniques all affect β-glucosidase activity (Pandey et al., 2014). The activity of this enzyme is decreased by increased solidity and salinity (Rietz and Haynes, 2003), as well as by soil depth (Xiao et al., 2018). Prior research indicates that in contrast to synthetic fertilizers and herbicides, vermicompost, compost from municipality solid waste material, and straw mulch raise β-glucosidase activity (Meyer et al., 2015). Microbial counts, the presence of organic materials, the use of mineral and organic fertilizers, tillage techniques (Banerjee et al., 2012), soil pH (Dick et al., 2000), crop rotation (Mukumbareza et al., 2015), water availability (Sardans and Penuelas, 2005), and heavy metal pollution (Kandeler et al., 1996) are some of the factors that affect phosphatase levels in agricultural practices. According to various studies, phosphatase activity measurement can be a useful indication of the accessibility of inorganic phosphorus for microbes and plants.

Table 1. Pattern of soil enzyme activities in various terrestrial ecosystems across India

S. No.	Soil enzymes	Land use pattern	Results	Seasonal pattern	Study area	References
1	Acid/alkaline phosphatase, β-glucosidases, ureases, and dehydrogenase activity	Forest land use, agricultural field, and vegetable field	Maximum enzymatic activity was found in forest land use	Maximum activity in monsoon season	Delhi	Meena and Rao (2021)
2	Acid/alkaline phosphatase, arylsulfatase, and dehydrogenase activity	Forest, Pasture, Apple, Saffron, and Paddy-Oilseed Plantation	Maximum enzymatic activity was found in forest land use	-	Northwestern Himalayas	Mir et al. (2023)
3	Acid/alkaline phosphatase, ureases, and dehydrogenase activity	Paddy filed study	-	Maximum activity in monsoon season	North Vanlaiphai, Mizoram	Vanlalveni and Lalfakzuala (2018)
4	Acid/alkaline phosphatase, arylsulfatase, nitrate reductase, phytase, and dehydrogenase activity	Oak, deodar, pine trees, orchid apples, and crop-based systems	All the enzymes show their maximum activity in forest land use	-	North-Western Himalayas	Singh et al. (2014)
5	Acid phosphatase, ureases, β-glucosidases, and dehydrogenase activity	Organic vs. unamended treated soil (in bell pepper)	Dehydrogenase activity is high in farmyard manure, acid phosphatase, and β-glucosidases are high in unamended control, and urease is high in the integrated crop management system.	-	Indian Himalayas	Gopinath et al. (2009)
6	Dehydrogenase activity	Forest soil and mine (coal) soil	Dehydrogenase activity, activity higher in forest land use	Maximum activity in autumn season	-	Kumar et al. (2013)
7	Alkaline phosphatase and dehydrogenase activity	Normal, sodic, and saline soils	Dehydrogenase activity and alkaline phosphatase activity are higher in normal soil	-	Indo-Gangetic plains of north-western India	Sharma et al. (2023)
8	Phenol oxidase, β-glucosidases, and dehydrogenase activity	Different ridges of Delhi	Forest land use have the maximum enzyme activity	Phenol oxidase maximum in post-monsoon, DHA in monsoon, β-glucosidases show inconsistent pattern	Delhi Ridges	Tomar and Baishya (2020)

Additionally, urease activity in the soil is greatly influenced by several factors, including tillage practices (Green et al., 2007), soil temperature (Fraser et al., 2013), soil moisture (Sardans and

Penuelas, 2005), soil pH (Blonska and Lasota, 2014), and organic fertilizers like compost, sewage sludge, and straw mulch (Meyer et al., 2015). Yang et al. (2006) studied the heavy metal pollution effect on urease activity and emphasized the sensitivity of urease to hazardous doses of heavy metals, with a special focus on the combined effects of lead, zinc, and cadmium. Soil dehydrogenase (DHA) enzyme is considered an intracellular enzyme that works on an oxido-reduction mechanism produced in microbial cells (Yuan and Yue, 2012) and is used as a benchmark of soil microbial activity, especially in semi-arid soils (Ros et al., 2003). Dehydrogenase activity and soil organic matter concentration are closely related. Increased microbial biomass can be supported by more substrate, which in turn can lead to increased enzyme synthesis (Yuan and Yue, 2012). In contrast, soluble organic matter may be introduced into wet soils by precipitation events, which may increase the number of bacteria present, resulting in high enzyme activity (Wolinska and Stepniewski, 2012).

Effects of heavy metal contamination on soil enzymes

Metal contamination caused by the toxic metals, also referred to as heavy metals, negatively affects the soil ecosystem and its products. Microbial characteristics, especially soil respiration rates and enzyme activity, are greatly impacted by trace metal contamination in soil (Aponte et al., 2020). However, by modifying the shape of proteins, changing the spatial arrangement of active groups, and competing with heavy metal ions necessary for the formation of complexes between the enzyme and the substrate. Heavy metals can directly disrupt the functions of enzymes (D'Ascoli et al., 2006; Kapoor et al., 2015). By interfering with microbial cells' RNA expression, Heavy metals can also prevent the synthesis of enzymes (Kapoor et al., 2015). Reduced enzyme synthesis and metabolic activity can result from this interaction, which can also prevent microorganisms from growing and reproducing.

Because specific microorganisms and enzymes collaborate within the energy and nutrient cycles of the soil ecosystem, the interaction between soil enzymes and microbes is essential for preserving soil health. According to research by Kandeler et al. (1996), soils tainted with metals like nickel (Ni), zinc (Zn), vanadium (V), copper (Cu), and cadmium (Cd) generally show decreased enzyme activity. But it's also important to note that elevated metal concentrations can occasionally be linked to changes in the makeup of microbial communities and increased enzyme activity, indicating that some microbial communities can adapt to or even flourish under harsh conditions (Chu, 2018). One of the simplest and least expensive methods for assessing soil contamination is the measurement of soil enzyme activity. Several investigations have been done regarding the effects of heavy metals on soil enzymes and their activities (Malley et al., 2006; Kapoor et al., 2015; Aponte et al., 2020). Enzymes have a preference for certain metals, which prevents them from doing their jobs. Due to its great mobility and minor affinity for soil extract. Additionally, various metals have varying effects on soil enzymes. Shen et al. (2005) discovered that Zn and Cd had a negative interaction because they were competing for the same active sites. Copper shows a decreasing effect on β-glucosidase than on cellulase activity (Geiger et al., 1998). According to Balyaeva et al. (2005), Pb significantly reduces enzyme activity, for instance, invertase, urease, catalase, and acid phosphatase activity.

Conclusion

Soil enzymes are important barometers to estimate the soil microbial activity and functioning and the effects of the climatic situation on the soil microbiota. Recognizing specific soil enzymes is crucial for effective monitoring of soil fertility and health in farmers' fields periodically with the aid of regional soil-testing laboratories. By identifying targeted enzymes, it is easy to address nutrient deficiencies and improve management practices to attain growth and yield. The soil is used as a source of enzymes for detecting specific substrates, and their availability offers a cost-effective approach. A diverse pool of soil enzymes can provide a more economical alternative for advancements in agriculture and environmental sustainability.

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ST conceptualized and wrote the original draft; AM reviewed the concept and evaluated the final draft; both authors approved the manuscript.

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