Journal of Natural Resource Conservation and Management
Vol. 5, No. 2, pp 124-136, 2024
doi: 10.51396/ANRCM.5.2.2024.124-136

Soil enzyme activities as bioindicators of soil health: Implications for sustainable agriculture

Nisha Singh[1,*], Asha[2], Vineet Kumar Maurya[3] and Deepak Singh[4,*]

[1]Department of Biochemistry, University of Lucknow, Lucknow-226007, Uttar Pradesh, India
[2]Department of Botany, University of Lucknow, Lucknow-226007, Uttar Pradesh, India
[3]Department of Botany & Microbiology, HNB Garhwal University (A central university), Srinagar (Garhwal) Uttarakhand, India
[4]ICAR-Indian Institute of Soil & Water Conservation, Dehradun, Uttarakhand, India
**Corresponding author email: nishasingh0711@gmail.com, dpk905@gmail.com*

Received : August 15, 2024
Revised : November 11, 2024
Accepted : November 14, 2024
Published : December 31, 2024

ABSTRACT

Soil health is the foundation of sustainable agriculture, influencing plant growth, nutrient cycling, and overall ecosystem functioning. Soil enzymes play an essential role in catalyzing crucial biochemical reactions within the soil, and their activity levels serve as sensitive indicators of soil quality and health. This review examines the relationship between soil enzyme activity and soil health, the major enzymes of interest, the factors influencing their activity, and their potential applications in sustainable agriculture. A comparative analysis of traditional physiochemical methods and enzyme-based approaches for evaluating soil health is presented, highlighting the enhanced sensitivity, efficiency, and ecological relevance of enzyme-based methods. Furthermore, the review highlights how soil enzyme activities can be employed as bioindicators for soil quality assessment and long-term soil health management.

Key words: Soil health, soil enzymes, sustainable agriculture, bioindicators, nutrient cycling

INTRODUCTION

Soil is a dynamic and complex system that plays an essential role in supporting life on Earth. It acts as a medium for plant growth, a reservoir for water and nutrients, and a habitat for countless organisms (Kumar, 2024). More than just a substrate for roots, healthy soil is integral to the sustenance of plants, animals, and humans. The concept of *soil health* has been defined as the capacity of soil to function as a living ecosystem to sustain biological productivity, promote environmental quality, and support plant and animal health (Maciejewska *et al*., 2024). Evaluating and understanding soil health is therefore critical for sustainable agricultural practices, ecological balance, and environmental conservation (Blanco *et al*., 2023).

Traditionally, soil health has been assessed using a variety of physical and chemical indicators. Parameters like soil texture, structure, pH, nutrient content, and organic matter are often analyzed to provide a picture of soil quality (Bangre *et al*., 2024; Singh *et al*., 2023). While these factors provide valuable information, they only reflect a part of the overall soil health picture. Soil is a living entity, and its biological properties, including the activity of soil microorganisms and the presence of enzymes, are equally important for determining its functionality and fertility (Hartmann and Six, 2023; Singh *et al*., 2022). The growing recognition of the importance of soil biology has led to a shift towards the use of biological indicators to provide a more comprehensive and accurate assessment of soil health (Kibret *et al*., 2023).

Traditional Soil Testing Methods

Physio-chemical Parameters for Soil Health Assessment

The physical properties of soil play a critical role in supporting plant growth by influencing water infiltration, root penetration, aeration, and soil structure (Singh *et al.*, 2021). Traditional soil health assessments often measure key physical parameters, such as soil texture, bulk density, structure, water-holding capacity, infiltration, and moisture content (Singh *et al.*, 2022). Soil texture, determined by the relative proportions of sand, silt, and clay, influences water-holding capacity, permeability, and nutrient retention. It is typically measured using sedimentation (hydrometer method) or by feel analysis (Callesen *et al.*, 2018). Bulk density, the mass of soil per unit volume including pore space, indicates soil compaction, affecting root growth and water movement; a lower bulk density is generally better for plant growth. Soil structure, referring to how particles form aggregates, influences infiltration, aeration, and root penetration and is assessed visually by examining the stability of aggregates (Singh *et al.*, 2023; Singh *et al.*, 2021). Water-holding capacity, influenced by texture and structure, is the soil's ability to retain water for plants, while infiltration is the rate at which water enters the soil, measured using pressure plate apparatus and double-ring infiltrometers, respectively. Soil moisture content, essential for plant growth and microbial activity, is determined by weighing soil before and after drying (Yang *et al.*, 2023).

Chemical properties are fundamental in understanding soil fertility, nutrient availability, and potential toxicity, with parameters like pH, electrical conductivity (EC), soil organic matter (SOM), cation exchange capacity (CEC), and nutrient content being crucial for assessing soil health (Singh *et al.*, 2022). Soil pH, measured using pH meters or strips, affects nutrient availability and microbial activity, with extreme acidity or alkalinity hindering plant growth (Pandao *et al.*, 2024). Electrical conductivity, indicating salinity level, is measured by assessing the resistance to an electrical current in a soil-water solution (Lech *et al.*, 2016). Soil organic matter, encompassing decomposed plant and animal residues, enhances structure and nutrient content, typically measured through the loss-on-ignition method (Condron *et al.*, 2010). Cation exchange capacity reflects the soil's ability to retain and exchange essential nutrients like calcium, magnesium, potassium, and ammonium, measured by saturating soil with a cation solution and analyzing absorbed ions (Mehlich, 1948). Nutrient content, crucial for plant growth, includes macronutrients (nitrogen, phosphorus, potassium) and micronutrients (iron, zinc, copper), determined through various chemical extraction methods such as the Kjeldahl procedure for nitrogen, Bray or Olsen methods for phosphorus, and ammonium acetate extraction for potassium (Pandey, 2018; Sαez-Plaza *et al.*, 2013; Irving and McLaughlin, 1990; Amorim *et al.*, 2021). These physical and chemical parameters collectively influence the soil's capacity to support healthy plant growth and productivity (Fig. 1).

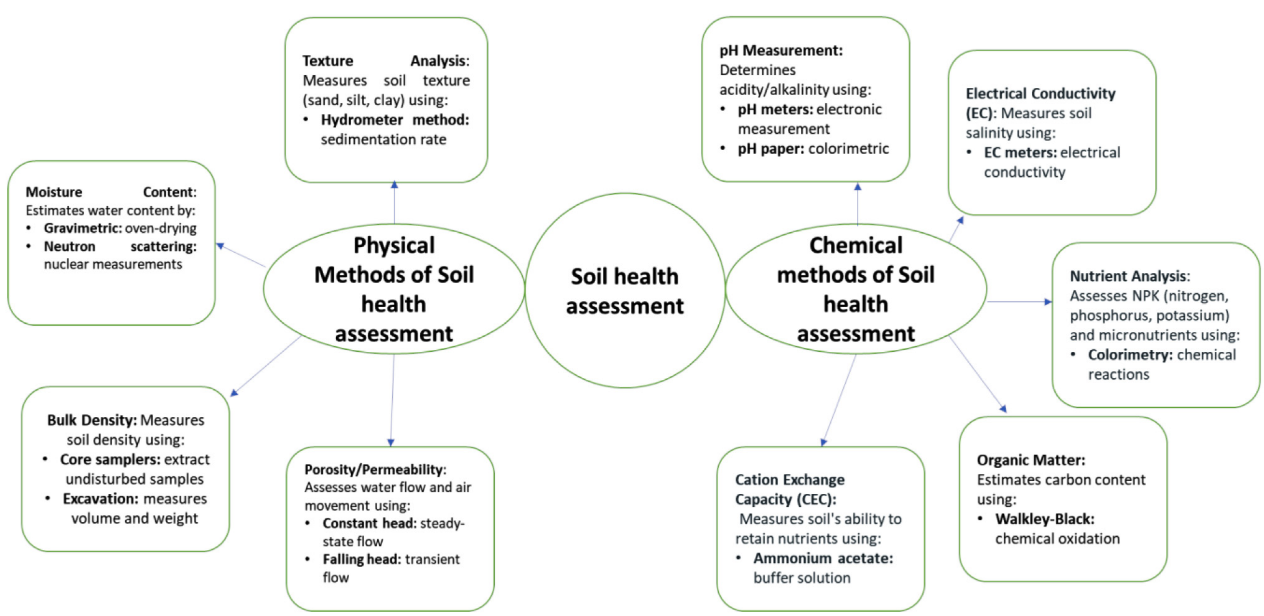

Fig. 1. Physical and chemical soil heath assessment methods

Soil Sampling and Laboratory Analysis

Traditional soil health assessment begins with soil sampling, which is often carried out at multiple depths and locations to obtain representative samples. These samples are then analyzed in the laboratory using standard methods for each parameter, such as titration for pH, EC meters for salinity, and colorimetric assays for nutrient analysis (Sarrantonio *et al.*, 1997).

On-Site Field Tests

In addition to laboratory analysis, several on-site tests provide rapid assessments of certain soil parameters. The penetrometer test measures soil compaction and resistance to root penetration by determining the force needed to push a probe into the soil, providing insight into soil density and potential barriers to root growth (Kumi *et al.*, 2023). Soil color and smell serve as visual and sensory indicators of organic matter content and soil health conditions, with darker soils generally indicating higher organic matter, and an earthy odor suggesting active microbial processes (Liebig and Doran, 1999). The aggregate stability test evaluates the quality of soil structure by observing how well soil aggregates remain intact when exposed to water, offering insights into erosion resistance, permeability, and overall soil health (Singh *et al.*, 2022; Singh *et al.*, 2021). These rapid on-site tests complement laboratory analyses to provide a holistic understanding of soil conditions.

Limitations of Traditional Soil Health Assessment

While physical and chemical parameters provide crucial information about soil health, they have limitations. One key limitation is the lack of biological indicators, as traditional assessments often overlook factors such as microbial activity and enzyme functions, which are critical for nutrient cycling, organic matter decomposition, and overall soil fertility (Cardoso *et al.*, 2013). Additionally, these assessments offer only a snapshot view of soil conditions at the time of sampling, failing to account for temporal variations and dynamic processes that influence long-term soil health. Moreover, parameters like pH, electrical conductivity (EC), and nutrient content offer insights into fertility but may not fully capture soil functionality, including its capacity to support sustainable agricultural practices, nutrient availability over time, and ecosystem resilience (Vanluwe *et al.*, 2015; Altomare *et al.*, 2011). These limitations highlight the need for integrated soil health assessments that consider physical, chemical, and biological aspects to gain a comprehensive understanding of soil quality.

The Need for Biological Indicators

The complexity of soil functions makes it challenging to rely solely on traditional measures for soil health assessment (Puig-Gironès and Real., 2022). To fully capture soil's multifaceted nature, biological indicators have been increasingly recognized for their capacity to provide valuable insights into soil functionality (Yoder and Rankin, 1998; Hellawell, 1986). These indicators include the presence and diversity of soil microorganisms (bacteria, fungi, protozoa), microbial biomass, soil respiration (carbon dioxide production), and enzyme activities. Among these, soil enzyme activities have emerged as particularly significant due to their direct involvement in key soil processes (Sinsabaugh, 2022).

Why Soil Enzymes?

Soil enzymes are organic catalysts primarily produced by soil microorganisms, plant roots, and soil fauna (Neemisha, 2022). They play a critical role in facilitating and accelerating biochemical reactions that drive the decomposition of organic materials and nutrient cycling. Enzymes such as phosphatases, ureases, dehydrogenases, and cellulases are involved in the breakdown of organic phosphorus compounds, urea, overall microbial respiration, and organic matter decomposition, respectively (Gianfreda and Ruggiero, 2006). Given their pivotal role in these processes, measuring enzyme activities provides a valuable lens through which soil health and functionality can be assessed (Fig. 2) (Das and Verma, 2011). The conversion of carbon (C), nitrogen (N), and phosphorus (P) sources into soluble compounds is crucial for soil processes, involving various enzymes. In addition to these, other microbial enzymes like dehydrogenases (DHA), catalases (CAT), phenol oxidases (PO), lipases (LIP), and carboxylesterases (EST) play significant roles in determining soil quality and serve as biological indicators of soil health (Gianfreda and Ruggiero, 2006; Das and Verma, 2011). The following subsections elaborate on the roles and importance of these key microbial enzymes.

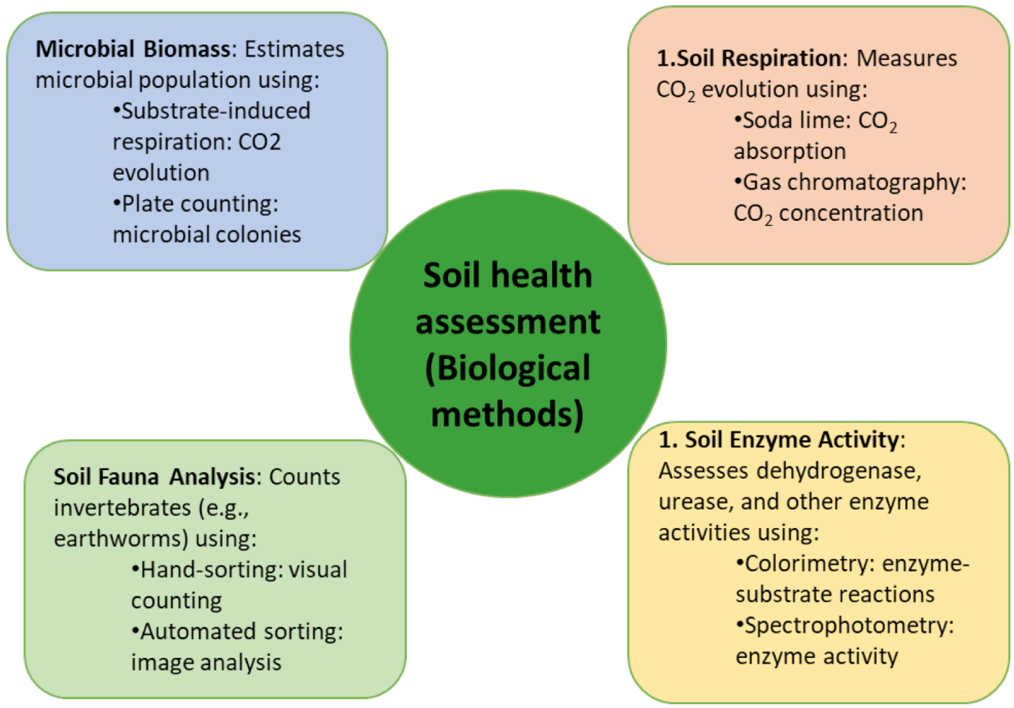

Fig. 2. Biological methods of soil heath assessment

Soil enzymes are highly sensitive to changes in soil conditions and management practices, responding rapidly to environmental stressors such as pH shifts, temperature fluctuations, organic matter content, and pollutant exposure (Utobo and Tewari, 2015). This sensitivity makes enzyme activities valuable bioindicators that reflect the biological status and health of soils in real time (Killham and Staddon, 2022). For instance, soil enzyme activities can indicate the impact of agricultural practices (e.g., tillage, fertilization, crop rotation) on soil health, as well as reveal the effects of pollutants like heavy metals, pesticides, or other contaminants (Sanga and Pius, 2024; Eclou and Glele Kakai, 2024).

Carbon-Cycling Enzymes

Carbon is a fundamental component of organic matter, and its cycling is essential for energy flow in soil ecosystems. The breakdown of carbon-rich compounds is mediated by enzymes that help release carbon in forms usable by soil microbes and plants (Wu, 2023). The vital role of β-Glucosidase in soil ecosystems is multifaceted. This enzyme, found in bacteria, fungi, actinomycetes, and plant roots, catalyzes the hydrolysis of β-D-glucosides, breaking down cellulose and other carbohydrate polymers into simple sugars like glucose (Geng *et al.*, 2023; Da Silva *et al.*, 2021). This process is essential for the carbon cycle, decomposing organic matter, and supporting microbial growth and activity. β-Glucosidases are abundant and crucial soil enzymes, exhibiting considerable variation due to the diversity of glycosidic bonds in their substrates (Barbosa *et al.*, 2023). Among glycosidases, α-glucosidase, β-glucosidase, α-galactosidase, and β-galactosidase are prominent, with β-glucosidase being particularly dominant. β-Glucosidase facilitates the hydrolysis reaction:

Glucoside + $H_2O \rightarrow$ ROH + Glucose.

Its key functions include cellulose breakdown, converting cellobiose residues to glucose, a key carbon source for soil microorganisms, influencing carbon cycling, soil organic matter, and biological activity, and decomposing maltose and cellobiose to produce glucose. However, its activity is influenced by several factors (De Almeida *et al.*, 2015). Research shows (Shah *et al.*, 2024) that β-glucosidase activity declines significantly with increasing soil pH, particularly in paddy soils, and is affected by soil moisture, with reductions leading to decreased activity. Elevated soil salinity and solidity also correlate with reduced activity. Moreover, soils enriched with organic material containing high C ratios and lignified roots exhibit lower β-glucosidase activity, while adding easily decomposable organic matter enhances its activity (Wei *et al.*, 2019).

Cellulase

Cellulase, produced by fungi (notably Trichoderma and Aspergillus species), bacteria (Bacillus spp.), and some actinomycetes, is a vital soil enzyme facilitating nutrient mobilization (Ahmed *et al.*, 2023). It breaks down cellulose, the primary structural component of plant cell walls, into glucose and other simple sugars, playing a crucial role in organic matter decomposition and the release of carbon from plant residues. Cellulase activity is essential for carbon cycling, influencing soil organic matter dynamics and biological activity, and releasing nutrients from plant residues for microbial growth and plant uptake (Faik, 2013; Khatoon *et al.*, 2017). Cellulase catalyzes the hydrolysis of cellulose into simpler sugars:

Cellulose → Cellobiose → Glucose.

Its activity in soil is affected by moisture, temperature, pH, organic matter quality, and microbial community diversity. Optimal moisture and temperature ranges (20-40°C) enhance cellulase activity, while pH levels between 5.5 and 7.5 support optimal activity. The presence and quality of organic matter also influence cellulase activity, with beneficial microbial communities promoting enzyme production. Cellulase plays a critical role in maintaining soil health by enhancing nutrient availability, promoting carbon cycling, supporting microbial growth and diversity, and facilitating organic matter decomposition (Santhanam *et al.*, 2012). Understanding cellulase activity informs agricultural practices, such as optimizing soil moisture and temperature, managing organic amendments, monitoring soil pH, and promoting beneficial microbial communities. Recognizing cellulase's significance in soil ecosystems enables better management of soil health, enhanced nutrient mobilization, and sustainable agricultural practices (Das and Varma, 2011). Effective cellulase activity is vital for maintaining soil fertility, supporting plant growth, and mitigating environmental issues like soil degradation and carbon emission (Jamir *et al.*, 2019).

Invertase

Invertases, also known by several other names such as β-fructosidase and sucrase, are carbohydrases that hydrolyze sucrose into D-glucose and D-fructose, forming "invert sugar" (Manoochehri *et al.*, 2020). This enzyme is related to the C cycle, indicating soil microbial activity and C metabolism intensity. INV cleaves α-1,2-glycosidic bonds in sucrose and operates under varying pH conditions, categorized as acidic, neutral, or alkaline. Its activity is primarily stimulated by the addition of organic matter, necessary for organic matter decomposition and humus synthesis (Trivedi *et al.*, 2016; Zhang *et al.*, 2023).

Polyphenol Oxidase and Peroxidase

Polyphenol Oxidase and Peroxidase are produced by bacteria (*Pseudomonas* spp.), fungi (*Basidiomycetes*), and plant roots, bacteria (*Bacillus* spp) (Kumar *et al.*, 2024). These enzymes degrade complex phenolic compounds, such as lignin, which is resistant to decomposition. By transforming phenolic structures into simpler compounds, these enzymes facilitate organic matter turnover and nutrient availability (Kumari *et al.*, 2024).

Nitrogen-Cycling Enzymes

Nitrogen is an essential nutrient for plant growth and soil fertility. Its cycling involves a series of complex transformations that make nitrogen available in various forms, including ammonium and nitrate.

Urease

Urease, an enzyme found in bacteria (e.g., *Proteus*, *Bacillus*), fungi, and some plants, plays a key role in nutrient mobilization. It hydrolyzes urea into ammonia and carbon dioxide, which is an essential step in nitrogen mineralization (Saleem *et al.*, 2023). This process makes nitrogen available to plants as ammonium, which can be further converted into nitrate by nitrifying bacteria. In soil ecosystems, urease catalyzes urea hydrolysis to release ammonium ions (NH_4^+) and bicarbonate, thus impacting the nitrogen cycle and influencing soil pH through ammonia (NH_2) volatilization (Chettri *et al.*, 2021). The main reaction catalyzed by urease is represented as:

Urea → $2NH_2 + CO_2$.

Urease activity is also vital in microbially induced calcium carbonate precipitation (MICP), which is beneficial for soil stabilization, self-healing, and erosion control. Additionally, urease activity serves as a significant indicator of soil quality and nitrogen management, with fluctuations due to organic fertilization, tillage, and environmental factors like temperature and soil characteristics (Veum *et al*., 2014).

Protease

Proteases are enzymes produced by various organisms, including bacteria (e.g., *Bacillus*, *Pseudomonas*), fungi (e.g., *Aspergillus*, *Penicillium*), and plant roots (Naveed *et al*., 2021). Their primary function in nutrient mobilization is to degrade proteins into peptides and amino acids. These breakdown products are then mineralized, releasing ammonium, which is crucial for converting organic nitrogen from plant and microbial residues into plant-available inorganic forms (Greenfield *et al*., 2020).

Nitrate Reductase

Nitrate reductase is an enzyme produced by a wide range of organisms, including plants, bacteria, fungi, yeast, and algae, playing a crucial role in nutrient mobilization and the nitrogen cycle (Beevers *et al*., 1983). This enzyme facilitates the reduction of nitrate (NO_3^-) to nitrite (NO_3^-), a key step in nitrogen assimilation, as nitrite is further reduced to ammonium (NH_4^+). The ammonium can be directly utilized by plants or incorporated into organic compounds such as amino acids and proteins, essential for growth and development. Among bacteria, *Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Staphylococcus aureus*, and *Klebsiella pneumoniae* are notable producers of nitrate reductase. Fungi such as *Aspergillus nidulans*, *Neurospora crassa*, and *Fusarium oxysporum* also exhibit this activity. Additionally, yeast like *Saccharomyces cerevisiae* (baker's yeast), algae like *Chlorella pyrenoidosa*, and soil bacteria such as *Rhizobia* contribute to nitrate reductase production (Kaviraj *et al*., 2024). These microorganisms express different types of nitrate reductase, including NADH-nitrate reductase, NADPH-nitrate reductase, and FMN-nitrate reductase, which play diverse roles in nitrogen metabolism, denitrification, assimilatory nitrate reduction, and dissimilatory nitrate reduction (Campbell, 2001). In the soil ecosystem, nitrate is a primary form of nitrogen available to plants, often originating from fertilizers, decomposing organic matter, or the nitrification process carried out by microbes. Nitrate reductase catalyzes the conversion of nitrate to nitrite within plant tissues, which is then rapidly reduced to ammonium by nitrite reductase (Bielek, 1998). This process not only supports plant growth and development but also integrates nitrogen into the food web, facilitating nutrient cycling across different trophic levels. In bacteria and fungi, nitrate reductase enables these microorganisms to use nitrate as a nitrogen source when preferred sources like ammonia are scarce. By reducing nitrate to nitrite, these organisms assimilate nitrogen for growth and metabolic needs. Moreover, in bacterial denitrification under anaerobic conditions, nitrate reductase can reduce nitrate to nitrogen gas (N,), releasing it back into the atmosphere and thereby completing the nitrogen cycle (Cabello *et al*., 2004). The enzyme's activity is regulated by factors such as nitrate availability, light, carbon metabolites, and environmental conditions like temperature and oxygen levels. The pivotal role of nitrate reductase in the nitrogen cycle supports plant growth, ecosystem health, and agricultural productivity while influencing soil fertility and nitrogen management.

β-1,4-N-Acetyl-Glucosaminidases (NAG)

Chitin degradation is facilitated by three main enzymes: lytic polysaccharide monooxygenase (LPMO), chitinase, and β-1,4-N-acetyl-glucosaminidase (NAG). LPMOs initiate degradation through oxidative action on crystalline chitin, resulting in chain breakage and oxidized ends, which are further processed by chitinases. Chitinases break glycosidic linkages, producing chitin oligosaccharides and dimers, while NAG completes the degradation, converting these products into N-acetylglucosamine, a key monomer for various metabolic processes (Daunoras *et al*., 2024). NAG activity is positively associated with soil organic carbon (C) and total N, and decreases with high inorganic N availability. It is also influenced by soil pH, functioning effectively in acidic, neutral, or slightly alkaline conditions based on its glycoside hydrolase family classification (Li *et al*., 2021). NAG plays an essential role in the conversion of chitin to mineralizable C and N, with its activity impacted by organic C content, total N, inorganic N levels, and soil pH.

Leucine aminopeptidases (LAP)

Leucine aminopeptidases are proteolytic enzymes from the M17 metallopeptidase family, hydrolyzing Leu residues from protein N-termini, along with a broad range of substrates including amino acids like Met, Ala, Arg, and Ile (Sanz, 2007). Optimal LAP activity is generally observed at pH 8–9 and varies based on the presence of divalent metal ions, with Mn²z being a commonly effective cofactor. LAP activity decreases with increased inorganic N supply and is susceptible to inhibition by cadmium (Cd), which impacts the enzyme's structure and active site. LAP is a key enzyme for nitrogen absorption in soil bacteria and is used to measure soil enzyme stoichiometry, providing insights into soil fertility and the effects of various compounds on soil health (Paul *et al.*, 2022).

Phosphorus-Cycling Enzymes

Phosphorus is a critical nutrient for plant growth, and its availability in soil is often limited due to its tendency to bind with minerals and organic compounds. Phosphatase enzymes play a key role in liberating phosphorus from these bound forms.

Phosphatases (Acid and Alkaline Phosphatases)

Phosphatases, including acid and alkaline phosphatases, are enzymes produced by various organisms such as bacteria (e.g., *Bacillus*, *Pseudomonas*), fungi (e.g., *Penicillium*, *Aspergillus*), mycorrhizal fungi (e.g., *Glomus* spp.), and plant roots. These enzymes play a crucial role in nutrient mobilization by catalyzing the hydrolysis of organic phosphorus compounds, leading to the release of inorganic phosphate-a readily available form for plant uptake. Acid phosphatases generally operate in acidic soils, while alkaline phosphatases function in neutral to alkaline soils, and their activity directly influences phosphorus availability, enhancing plant nutrition. Phosphatases are particularly critical for organic phosphorus (P) mineralization, especially in tropical soils (Sharma *et al.*, 2006). They hydrolyze phosphomonoesters (and occasionally phosphodiesters) to release phosphate, as represented by the reaction:

Phosphate ester + $H_2O \rightarrow ROH + PO_4^-$.

This process effectively converts organically bound phosphorus into inorganic forms that plants can utilize. The activity of phosphatases is influenced by several factors, including soil pH, drought conditions, and the application of organic amendments. Specifically, acid phosphatase (AcP) is more active in acidic soils, while alkaline phosphatase (AlP) predominates in alkaline soils (Millan, 2006). Environmental factors such as the presence of heavy metals or amendments can significantly impact phosphatase activity, either inhibiting or enhancing the enzyme's function. As a result, phosphatases are key to maintaining soil phosphorus balance, ensuring the mineralization of organic P, and ultimately supporting healthy plant growth and nutrition.

Phytase

Phytase is an enzyme produced by various organisms, including microorganisms (e.g., *Aspergillus*, *Bacillus*), mycorrhizal fungi, and plants. Its primary function in nutrient mobilization is to hydrolyze phytate, an organic form of phosphorus stored in plant tissues, into inorganic phosphate. This process is especially crucial in soils where phosphorus is predominantly bound in organic complexes, as phytase increases the bioavailability of phosphorus, allowing for greater plant uptake and utilization (Singh and Satyanarayana, 2011).

Sulfur-Cycling Enzymes

Sulfur is an essential macronutrient for plants, involved in the synthesis of amino acids and proteins. The transformation of sulfur in the soil is mediated by enzymes that break down organic sulfur compounds.

Arylsulfatase

Arylsulfatase is an enzyme produced by bacteria (e.g., Pseudomonas), fungi (e.g., Aspergillus), and plant roots, playing a pivotal role in nutrient mobilization by catalyzing the hydrolysis of sulfate esters. This process releases sulfate (SO_4^{2-}), a form of sulfur that plants can readily assimilate (Stressler *et al.*, 2016). The activity of arylsulfatase is crucial for the mineralization of organic sulfur compounds, enhancing sulfur availability for plant growth. Sulfatases, including arylsulfatase (ARS), significantly contribute to the sulfur (S) cycle by breaking down organic sulfur compounds to release sulfate. The reaction catalyzed by ARS is represented as follows:

$ROSO_4^- + H_2O \rightarrow ROH + SO_4^{2-}$.

This reaction is fundamental in converting organically bound sulfur into inorganic sulfate, which is essential for plant nutrition. The production and activity of ARS are influenced by soil microorganisms in response to sulfur availability, and its presence is often an indicator of sulfur mineralization and microbial activity in soils (Saha *et al.*, 22018). Consequently, ARS plays a vital role in maintaining soil sulfur balance and promoting optimal conditions for plant growth and health.

Enzymes Involved in Soil Structure and Organic Matter Decomposition

Beyond nutrient cycling, certain soil enzymes contribute to the formation of soil structure and the overall turnover of organic matter, indirectly influencing nutrient availability.

Amylase

Amylase is an enzyme produced by bacteria (e.g., *Bacillus* spp.), fungi (e.g., *Aspergillus* spp.), and plants, which plays a key role in nutrient mobilization by catalyzing the breakdown of starch into simpler sugars like maltose and glucose. This enzymatic activity contributes to the decomposition of plant residues, thereby promoting carbon cycling in the soil ecosystem (Senthilkumar *et al.*, 2012). The breakdown of starch not only releases sugars that can be utilized by soil microorganisms for energy but also enhances soil fertility and supports the overall nutrient availability for plant growth.

Lipase

Lipase is an enzyme produced by bacteria (e.g., *Pseudomonas*, *Bacillus*), fungi (e.g., *Penicillium*), and plant roots, playing a vital role in nutrient mobilization by hydrolyzing lipids into fatty acids and glycerol. This enzymatic process is crucial for the decomposition of plant and microbial cell membranes, thereby facilitating the recycling of carbon and other nutrients. The breakdown of lipids not only contributes to soil carbon cycling but also enhances nutrient availability for both micro-organisms and plants, supporting soil fertility and ecosystem health.

Factors Influencing Soil Enzyme Activity

Soil enzyme activity is affected by several biotic and abiotic factors, including soil temperature, moisture, pH, organic matter content, and microbial community structure. Management practices like crop rotation, tillage, organic amendments, and fertilization also play a significant role in modulating enzyme activity (Xu *et al.*, 2015). Organic matter content provides substrates for microbial growth and enzyme production, supporting diverse microbial communities and enhancing enzyme activity through increased carbon and nutrient availability. Soil pH affects enzyme structure and function, influencing substrate availability and affinity, with different enzymes having optimal pH ranges. For instance, acid phosphatase thrives in acidic soils, while alkaline phosphatase excels in neutral to alkaline soils (Xu *et al.*, 2015).

Soil moisture and temperature also play crucial roles. Moisture facilitates substrate and enzyme movement, maintaining enzyme conformation and activity, while extreme dryness reduces enzyme activity (Shah *et al.*, 2024). Temperature affects enzyme activity, with optimal temperatures between 20-40°C, and high temperatures potentially denaturing enzymes. Crop rotation alters microbial communities by changing crop residues and root exudates, supporting diverse microbial communities that produce a wider range of enzymes (Wei *et al.*, 2019). Tillage incorporates organic matter, increasing substrate availability, but excessive tillage disrupts microbial communities, reduces moisture, and increases oxygen exposure, potentially reducing enzyme activity. Organic amendments provide additional substrates for microbial growth and enzyme production, enhancing nutrient cycling and availability. Balanced fertilization provides essential nutrients for microbial growth and enzyme production, avoiding excessive application that can inhibit enzyme activity (Singh *et al.*, 2023; Xu *et al.*, 2015). Optimizing these factors supports beneficial microorganisms, promotes enzyme activity, and maintains optimal soil conditions for plant growth and ecosystem functioning. Effective management practices consider these interacting factors to enhance soil enzyme activity, facilitating nutrient cycling and promoting soil health.

Soil Enzyme Activity as a Predictor of Soil Health

Soil enzyme activities are increasingly seen as reliable predictors of soil health because they directly mediate the processes that sustain soil fertility and functionality (Table 1). By assessing enzyme activities, it is possible to infer the biological status of soils, the activity and diversity of soil microorganisms, and the potential for nutrient availability and cycling. Enzyme activities respond quickly to changes in soil conditions, allowing for the rapid detection of disturbances or management

Table 1 Comparative analysis of Soil Enzyme Activity vs. Traditional Physicochemical Parameters based Assay

Criteria	Soil Enzyme Activity based Soil Health Prediction	Traditional Physicochemical Parameters based soil health Prediction
Parameter Type	Biological	Chemical/Physical
Direct Biological Relevance	High - directly linked to microbial activity and nutrient transformations	Moderate - indirectly related to biological processes
Sensitivity to Environmental Changes	Very sensitive - rapid response to environmental changes	Less sensitive - slower response to environmental changes
Influence on Nutrient Cycling	Strong influence on C, N, P, and S cycling	Limited influence - serves as baseline indicators for nutrient availability
Response Time to Soil Management	Rapid - responds quickly to soil management practices	Slow - changes are often detected over longer periods
Measurement Complexity	Moderate - requires specific protocols and laboratory conditions	Low - straightforward standard protocols and measurements
Cost and Time Efficiency	Moderate - specialized assays are required but can be efficiently executed	High - routine soil tests are cost-effective and quick
Indicators of Soil Fertility and Health	Strong indicator - directly reflects biological health and processes in the soil	Moderate indicator - shows chemical status but not biological function
Utility in Sustainable Agriculture	Highly useful - provides insights into soil microbiome and organic matter transformations	Moderately useful - good for assessing nutrient availability and basic soil properties

interventions. This makes enzyme assays particularly valuable for monitoring soil health over time and across different land-use practices. Measuring soil enzyme activities is a non-destructive process, meaning it does not alter the soil structure or composition (Chaer *et al.*, 2009). This allows for repeated measurements over time without impacting the soil's natural state. Soil enzyme assays are generally cost-effective and can be performed relatively easily in a laboratory setting. They provide a practical approach to soil health assessment, particularly when combined with other biological and chemical indicators. Because enzymes are directly involved in nutrient cycling and organic matter decomposition, their activities are reflective of the overall soil health and its ability to sustain plant growth. Higher enzyme activity generally correlates with more active and diverse microbial communities and better soil fertility (Raiesi and Beheshti, 2014).

Applications in Soil Health and Sustainable Agriculture

Soil enzyme activities have broad applications in assessing the impacts of agricultural practices on soil health (Fig. 3). By measuring enzyme activities associated with carbon, nitrogen, and phosphorus cycling, it is possible to evaluate the soil's capacity to release nutrients that are crucial for plant growth. Soil conservation practices, such as reduced tillage, organic farming, crop rotation, and cover cropping, have been shown to enhance soil enzyme activities, reflecting improved soil structure, increased organic matter, and enhanced biological fertility (Das and Varma, 2011). Soil enzyme activities can also serve as indicators of soil recovery during bioremediation of contaminated soils. For example, the restoration of enzyme activities such as dehydrogenase or phosphatase can indicate the successful reestablishment of microbial communities and soil functionality after heavy metal or pesticide contamination (Gómez-Sagasti *et al.*, 2012).

CONCLUSION

The shift towards biological indicators in soil health assessment represents an important step in understanding and managing soils as living systems. Soil enzyme activities, as sensitive, dynamic, and reflective indicators of biological processes, provide valuable insights into the state of soil health. By evaluating enzyme activities in conjunction with other biological, physical, and chemical indicators, a more holistic understanding of soil health can be achieved. This comprehensive assessment is essential for promoting sustainable agricultural practices, enhancing soil fertility, and ensuring long-term soil

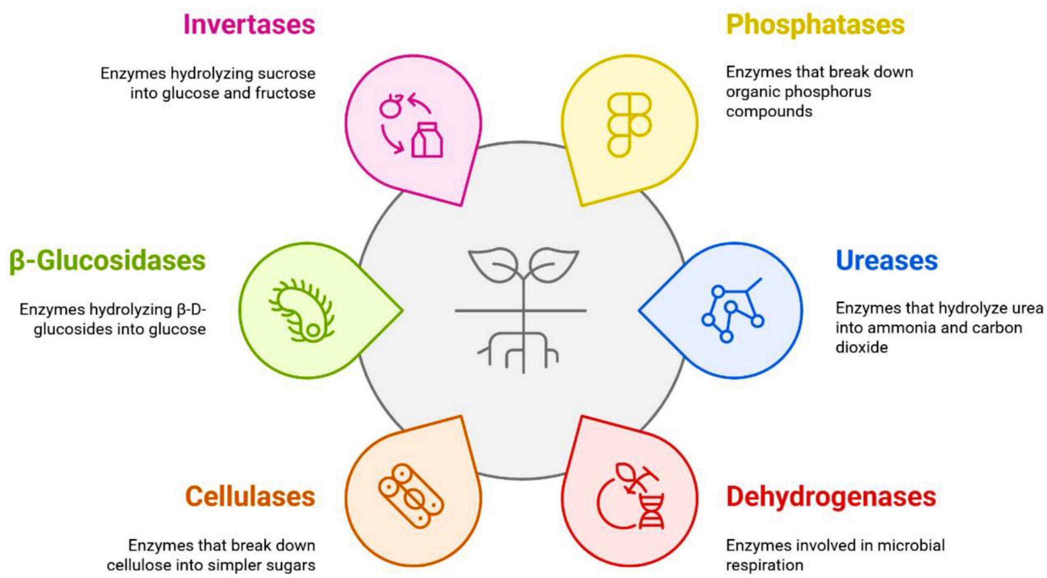

Fig. 3. Role of soil enzymes on soil health

productivity and environmental conservation. The integration of soil enzyme activities into soil health assessment frameworks offers significant potential for developing sustainable land management strategies. Future research and innovation in this field will continue to enhance our ability to monitor and improve soil health, thereby contributing to sustainable agriculture and ecosystem resilience. Soil health is defined as the capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. Its evaluation is critical for ensuring sustainable agricultural production, environmental conservation, and ecological balance. Traditional methods for assessing soil health often rely on physical and chemical parameters, but biological indicators are increasingly recognized for providing a more comprehensive understanding of soil quality. Among these, soil enzyme activities have emerged as significant indicators due to their involvement in various soil processes.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the technical and support staff for help.

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