Use of Mycorrhiza Fungi to Improve Soil Phosphorus Availability in Sustainable Agriculture

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***Abstract*— Phosphorus is one of the essential nutrients for plant growth and development. However, most of the phosphorus in soils is not directly available for uptake by plants. A large proportion of phosphorus is bound to organic compounds or insoluble inorganic forms and this leads to a significant productivity problem, especially in sustainable agricultural practices. In this study, methods to increase phosphorus availability in soil were discussed and the role of arbuscular mycorrhizal fungi in this process was examined. Mycorrhizal fungi establish symbiotic relationships with plant roots to increase phosphorus uptake from soil and also provide many agronomic benefits such as water uptake, root development and plant resistance. As an alternative to the environmental and economic drawbacks of conventional fertilisation practices, mycorrhiza applications have great potential to improve phosphorus management in sustainable agricultural systems. In this context, the dissemination of mycorrhiza biotechnology and a better understanding of soil-plant-microorganism interactions will enable the development of integrated approaches that improve phosphorus efficiency.**

***Keywords*—Mycorrhiza, Phosphorus, Sustainable Agriculture.**

I. Introduction

Phosphorus is recognised as the second most important macro element after nitrogen for plant growth and development. However, only a small fraction (0.1-0.5%) of the total phosphorus present in agricultural soils is in a form that can be directly utilised by plants [1]. Most of the remaining phosphorus is present as insoluble complexes such as calcium, iron and aluminium phosphates, which limits the effectiveness of phosphorus fertilizers. Most of the phosphorus applied in agricultural soils is rapidly transformed into insoluble forms and cannot be taken up by plants. This situation both limits plant yields and increases environmental risks by encouraging the use of high phosphorus fertilizers [2]. In addition, excessive and irregular use of chemical phosphorus fertilizers leads to both economic losses and environmental problems [3].

In this context, phosphorus solubilising microorganisms are becoming increasingly important in the development of sustainable agricultural systems. Various species of bacteria and fungi, such as Pseudomonas, Bacillus, Rhizobium, Aspergillus and Penicillium, can solubilise insoluble phosphates in soil through organic acids, enzymes or proton secretion, making them available to plants [4]. These microorganisms are considered as an important component of plant growth-promoting biofertilizers and are particularly noted for their potential to improve phosphorus utilisation efficiency.

The limited availability of phosphorus resources worldwide has made phosphorus management a strategic issue for agricultural sustainability in the long term. Increasing phosphorus utilisation efficiency, reducing losses and developing recovery methods are among the current research topics [5]. The use of phosphorus solubilising organisms in agriculture is seen as a promising technical application that both contributes to more efficient utilisation of phosphorus resources and serves environmental sustainability by reducing the need for chemical fertilizers. In this study, studies on the use of phosphorus solubilising microorganisms in agriculture and their environmental impacts were evaluated.

II. Methods To Increase Phosphorus Availability In Soil

Phosphorus is a macronutrient element vital for plant growth and development. Increasing phosphorus availability in soil is very important for improving plant nutrition and increasing fertilizer efficiency. However, most of the phosphorus in soil is in insoluble form and cannot be taken up directly by plants. Some special characteristics of soils significantly limit the availability of soil phosphorus, create difficulties in phosphorus nutrition of plants and significantly increase production costs. Commonly used methods and techniques to increase soil phosphorus availability are summarised below:

A. Mineral Phosphorus Fertilizer Applications:

Phosphorus-rich fertilizers such as triple super phosphate (TSP) and diammonium phosphate (DAP) can be applied directly to increase the amount of useful phosphorus in the soil. However, these fertilizers can rapidly bind with Fe, Al or Ca in the soil and precipitate [6].

B. Organic Matter Applications

Organic matter (compost, farmyard manure, green manures) can solubilise phosphorus by increasing microbial activity in the soil. In addition, organic acids release phosphorus by complexing with Al, Fe and Ca, which retain phosphorus [1].

2.3 Regulation of Soil pH: Soil pH directly affects the solubility of phosphorus. Phosphorus has the highest solubility between pH 6.0-7.0. Al and Fe phosphates are formed in acidic soils and Ca phosphates are formed in alkaline soils, rendering phosphorus useless to plants [7].

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C. Suitable Fertilizer and Fertilisation Techniques

The application of phosphorus fertilizers close to the root zone (band application) significantly increases the availability of phosphorus. If phosphorus is sprinkled on the surface, it is more likely to react with soil components and become unavailable [8]. Slow-release phosphorus fertilizers release phosphorus slowly, allowing it to spread into the soil and remain useful to the plant for a longer period of time. It reduces phosphorus losses especially in areas with heavy rainfall. Nano-sized phosphate fertilizers dissolve faster and are used more effectively by plants thanks to their large surface area [9].

III. Phosphate Solubilising Microorganisms

In soil, phosphorus is usually present as insoluble compounds such as phosphates of calcium, iron and aluminium. Therefore, it can be rapidly depleted around the roots and is slow to reach the roots by re-localisation. This limited mobility makes it difficult for phosphorus to be effectively taken up by plants.

Phosphate solubilising microorganisms are microorganisms that physically dissolve insoluble phosphorus compounds and increase phosphorus uptake by plants and play an important role in sustainable agricultural practices [10]. Phosphorus solubilising microorganisms include various bacterial and fungal species. Among these, species such as Mycorrhiza, Pseudomonas, Bacillus, Rhizobium, Aspergillus and Penicillium stand out. These microorganisms have the ability to degrade both organic and inorganic phosphate compounds [11]. These microorganisms lower the pH by secreting organic acids and ensure the dissolution of phosphate ions. They also help the release of phosphorus by chelating phosphate-bound metal ions [12]. Among these organisms, especially arbuscular mycorrhizal fungi (AMF) provide nutrients, especially phosphorus, to reach plants more effectively [13].

AMF are fungi that form symbiotic relationships with plant roots and enhance plant uptake of nutrients with low mobility, especially phosphorus, zinc and copper. AMF do not directly solubilise phosphate, but work in symbiosis with organic acid-secreting bacteria to mobilise phosphorus. Furthermore, fungal hyphae can chelate phosphate ions, increasing its solubility [14]. By greatly increasing root surface area, mycorrhizal fungi mobilise phosphorus from soil areas inaccessible to roots and transport it to the roots. This markedly improves plant growth, especially in soils with low phosphorus content [13, 15]. AMFs enter plant root cells and form specialised branched structures called arbuscules. These structures are the points where the fungus exchanges substances with the plant. With their branched structures, arbuscules increase the surface area for nutrient exchange and significantly increase phosphorus uptake by mobilising and transporting low-solubility inorganic phosphorus sources inaccessible to plants. The amount of this increase varies depending on soil type, plant species, mycorrhiza type and environmental conditions, but studies have reported phosphorus uptake increases averaging between 30% and 80%. AMFs also reduce stress damages by stimulating antioxidant defence systems in plants under environmental stress conditions such as drought, salinity and heavy metal pollution [16].

IV. Use Of Mycorrhiza In Sustainable Agriculture

The use of mycorrhizal fungi in sustainable agriculture plays a critical role in plant nutrition and health, soil quality protection, carbon sequestration, reduced need for chemical inputs and environmental sustainability.

A. Agricultural and Environmental Sustainability

Sustainable agriculture aims at environmentally friendly, economically viable and socially acceptable farming systems. Mycorrhizal fungi play an important role in achieving this goal because they both optimise plant nutrition and reduce environmental impacts. Mycorrhiza enable plants to utilise nutrients with limited mobility, especially phosphorus, more efficiently. This reduces the need for phosphorus fertilizer and prevents the use of excess fertilizer, which accumulates in the soil and pollutes the environment. In this context, the use of AMFs in agricultural applications contributes to environmental sustainability by reducing the use of chemical fertilizers[13].

B. Soil Health

Mycorrhizal fungi improve soil structure by promoting soil aggregation through the hyphae network, thereby increasing water holding capacity and air permeability. It also supports microbial diversity. Mycorrhizae produce a glycoprotein called glomalin, which improves soil structure. Mycorrhiza-derived glomalin improves soil physical structure by binding soil particles, reduces erosion risk, promotes carbon storage and contributes to sustainable soil health [17].

C. Plant Stress Tolerance

Mycorrhiza makes plants more resistant to environmental stresses such as drought, salinity and heavy metal pollution. This enables sustainable production in the face of challenges such as climate change [18].

D. Ecosystem Services

Mycorrhiza increases both biodiversity and productivity by establishing a balance between plant communities. It strengthens ecosystem services (nutrient cycling, carbon sequestration, etc.) by supporting plant diversity and soil functionality. This provides the basis for long-term agricultural production. AMFs establish symbiotic relationships with more than 80 per cent of the world's plants. The use of AMFs in low-input organic farming practices is particularly important to reduce the use of chemical fertilizers and support soil biology [19].

V. Mycorrhiza Production

AMFs are difficult to culture organisms that require living root tissue to complete their life cycle. For this reason, they are used in agricultural applications as inoculants in the form of commercial products. The production of mycorrhizal fungi as ‘inoculum’ refers to the multiplication of these fungi in the form of inoculum (vaccine material) and making them applicable to plants. AMFs in particular are obligate biotrophs, meaning that they can only reproduce in symbiotic relationships with living plant roots. Therefore, they must be produced together with plants under laboratory or greenhouse conditions. Soil-based (substrate-based), aeroponic/hydroponic-based and in vitro root organ culture-based methods are used in the production of AMF vaccines and can be prepared in solid, liquid and granular forms.

VI. Challenges In Field Application Of Phosphorus Solubilising Organisms

Phosphorus solubilising organisms stand out as an environmentally friendly biofertilizer option that supports plant growth by increasing the solubility of phosphate. However, the successful results obtained in laboratory and greenhouse environments are often not as effective as expected due to various biotic, abiotic and application-related difficulties. The main reasons for this situation are explained below:

A. Microbial Competition and Soil Ecology

Microorganisms grown under sterile or low competition conditions in the laboratory undergo intense competition with the resident microbial communities present in field soils. This can make it difficult for inoculated AMF strains to establish and operate effectively in the rhizosphere [20]. For AMF applications to be effective under field conditions, locally adapted strains should be selected.

B. Effect of Environmental Factors

The efficacy of AMFs is strongly dependent on environmental factors such as temperature, soil pH, moisture, salinity and organic matter content. While these factors are controlled under laboratory and greenhouse conditions, they are highly variable under field conditions. This can directly affect the phosphorus solubilising capacity of the microorganism [21].

C. Effect of Soil Structure and Phosphorus Forms

In field soils, phosphorus is usually found as calcium, iron or aluminium complexes. Since more easily soluble phosphate salts are generally used in laboratory tests, the results obtained are not exactly reflected in the field. In addition, soil texture (sandy, clayey, etc.) affects the mobility and effect of AMF [22].

D. Application Methods and Selection of Carrier Material

The method of application of microbial inoculants (seed coating, liquid application, soil sprinkling, etc.) and the carrier materials used (peat, lignite, vermiculite) play a major role on the survival time and effectiveness of the microorganism. During application, AMFs can be exposed to UV light, drought and physical stresses [23]. Therefore, it is necessary to develop site-specific application protocols using appropriate carrier systems.

E. Plant-Microbe Compatibility and Strain Selection

AMFs are not compatible with every plant. A successful strain in the laboratory may not form effective symbiosis with different plant species in the field. Therefore, strain selection specific to local conditions and plant species is of great importance [24].

VII. Conclusion

Making soil phosphorus available to plants is a critical agricultural issue in terms of both productivity and the environment. While chemical fertilisation offers short-term solutions, biological approaches such as mycorrhiza offer long-term sustainable and environmentally friendly options. Phosphate solubilising microorganisms are important biological agents that increase phosphorus efficiency in agricultural production and support environmental sustainability. The use of these microorganisms provides both economic and ecological benefits. Arbuscular mycorrhizal fungi are important microorganisms that offer multifaceted benefits ranging from plant growth to soil health, ecosystem services to agricultural sustainability, and their role in soil phosphorus mobilisation is being considered as a key strategy for future phosphorus management. Moreover, considering other plant growth-promoting effects of AMFs (such as phytohormone production, resistance to biotic and abiotic stresses), the use of these microorganisms in biofertilizer formulations is becoming an indispensable element in integrated agriculture approaches. However, due to some difficulties in the direct transfer of successful results obtained in laboratory and greenhouse conditions to the field, there is a need for further field studies to increase the effectiveness of AMFs in different soil and climatic conditions and to evaluate local microbial resources.

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