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Isolation and Characterization of Phosphate Solubilizing Microorganisms from Natural Soil Resources and Their Role in Crop Production Enhancement.

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ABSTRACT:
Phosphate solubilizing microorganisms (PSMs) play a crucial role in enhancing crop production by making phosphorus more available to plants. This study focuses on isolating and characterizing PSMs from natural soil resources and evaluating their potential in crop production enhancement. The methodology involved the collection and processing of soil samples followed by the isolation of PSMs using selective media. The isolated strains were then characterized morphologically, biochemically, and molecularly using techniques such as PCR and sequencing. Additionally, their functional capabilities in phosphate solubilization were assessed through biochemical assays. The results revealed a diverse population of PSMs present in the soil resources, exhibiting varied morphological and biochemical characteristics. Molecular identification confirmed the presence of various genera including Bacillus, Pseudomonas, and Enterobacter among others. Functional assays demonstrated the phosphate solubilization potential of the isolated strains, indicating their ability to enhance phosphorus availability in soil. The discussion highlights the significance of PSMs in agricultural systems and their potential applications in crop production enhancement. The diversity and functional attributes of the isolated PSMs underscore their importance as biofertilizers for sustainable agriculture. This research contributes to the understanding of soil microbial communities and provides insights into harnessing their potential for improving nutrient availability and crop productivity. Future research directions include exploring the synergistic effects of PSMs with other beneficial microorganisms and optimizing their application strategies for maximum agricultural benefits.

Keywords:
Solubilizing, Microorganisms

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I.**Introduction**:

In agricultural ecosystems, the availability of essential nutrients, particularly phosphorus, plays a pivotal role in determining crop productivity and sustainability. Phosphorus is a critical element involved in various biochemical processes within plants, including photosynthesis, energy transfer, and nucleic acid synthesis. Despite being abundant in soil, phosphorus often exists in insoluble forms, rendering it inaccessible to plants. This limitation necessitates the development of strategies to enhance phosphorus availability and uptake by plants, thereby optimizing crop yields and ensuring food security.

A. Background:

Phosphorus (P) is one of the primary macronutrients required for plant growth and development, alongside nitrogen (N) and potassium (K). It plays a crucial role in several physiological processes, serving as a component of nucleic acids, phospholipids, and adenosine triphosphate (ATP), the energy currency of cells [1]. Phosphorus deficiency can severely impair plant growth, leading to stunted development, poor root formation, and decreased reproductive capacity. Consequently, addressing phosphorus limitation is imperative for sustaining agricultural productivity and meeting the demands of a growing global population. In natural soil environments, phosphorus exists predominantly in insoluble forms, such as apatite minerals, iron (Fe) and aluminum (Al) phosphates, and organic matter complexes. These forms exhibit low solubility and limited availability for plant uptake, especially in acidic or alkaline soils where phosphorus fixation occurs. As a result, conventional phosphorus fertilizers are often applied to agricultural soils to supplement plant requirements [2]. Excessive fertilizer use can lead to environmental pollution, eutrophication of water bodies, and soil degradation, necessitating more sustainable approaches for managing phosphorus in agro ecosystems.

B. Importance of Phosphorus in Crop Production:

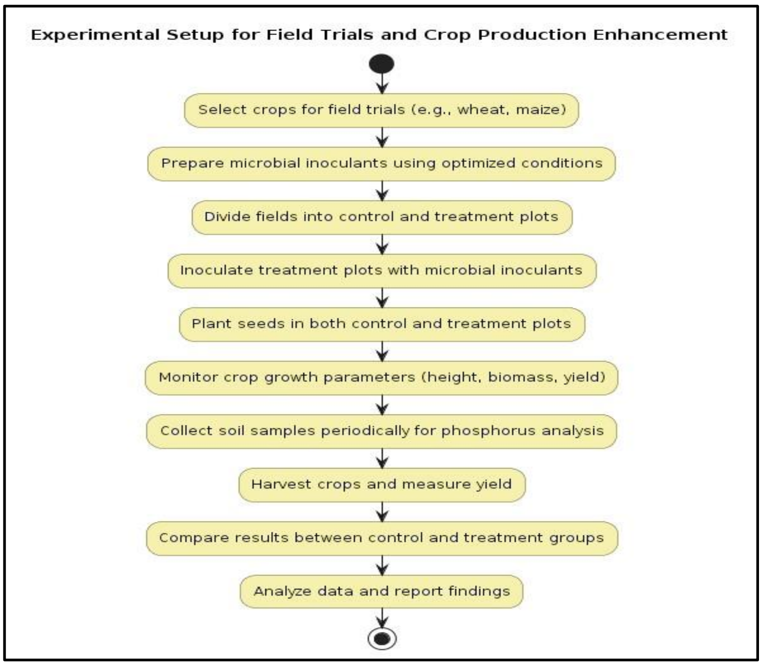

Figure 1: Experimental Setup for Field Trials and Crop Production Enhancement

Phosphorus deficiency is a common limitation to crop productivity worldwide, particularly in soils with alkaline pH or high levels of calcium (Ca) and magnesium (Mg). Inadequate phosphorus availability can result in reduced crop yields, posing significant challenges to agricultural sustainability and food security. Moreover, the finite nature of phosphorus reserves and the energy-intensive process of phosphate rock mining highlight the need for efficient phosphorus management practices in agriculture [3]. Phosphorus plays a crucial role in root development, nutrient uptake, and plant metabolism, influencing various aspects of crop growth and yield formation. It is particularly important during the early stages of plant growth, where phosphorus deficiency can delay root initiation and limit nutrient acquisition. Phosphorus deficiency can impair reproductive processes, leading to decreased seed production and poor crop quality [4]. Ensuring an adequate supply of phosphorus is essential for maximizing crop yields and optimizing resource use efficiency in agricultural systems.

C. Role of Phosphate Solubilizing Microorganisms (PSMs):

Phosphate solubilizing microorganisms (PSMs) are a diverse group of bacteria and fungi capable of converting insoluble phosphorus compounds into soluble forms through various mechanisms. These microorganisms play a crucial role in soil phosphorus cycling and contribute to the bioavailability of phosphorus for plant uptake. PSMs employ different strategies to solubilize phosphorus, including the production of organic acids, chelation of metal ions, and secretion of phosphatase enzymes.

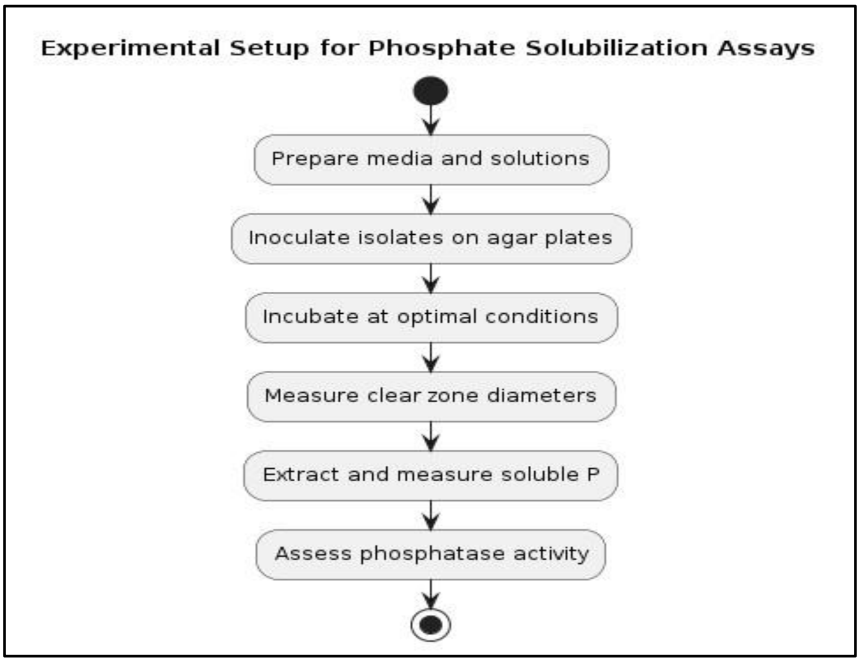

Figure 2: Detailed Characterization and Identification Workflow

By enhancing phosphorus availability in the rhizosphere, PSMs promote root growth, nutrient uptake, and overall plant health. The isolation and characterization of PSMs from natural soil resources offer promising opportunities for sustainable agriculture and environmental management.

These microorganisms possess the inherent ability to mobilize phosphorus from insoluble pools [5], thereby reducing the reliance on chemical fertilizers and mitigating the environmental impacts associated with phosphorus runoff. Moreover, PSMs exhibit diverse functional traits and metabolic capabilities, making them valuable candidates for biofertilizer development and soil health improvement. Addressing phosphorus limitation in agricultural systems is essential for achieving global food security and sustainable development goals.

The isolation and characterization of phosphate solubilizing microorganisms from natural soil resources represent a promising approach for enhancing phosphorus availability and optimizing crop productivity. This research aims to explore the diversity, distribution [6], and functional attributes of PSMs and their potential applications in agricultural practices. By elucidating the role of PSMs in soil phosphorus cycling and crop production enhancement, this study contributes to the advancement of sustainable agriculture and environmental stewardship.

II.Methodology:

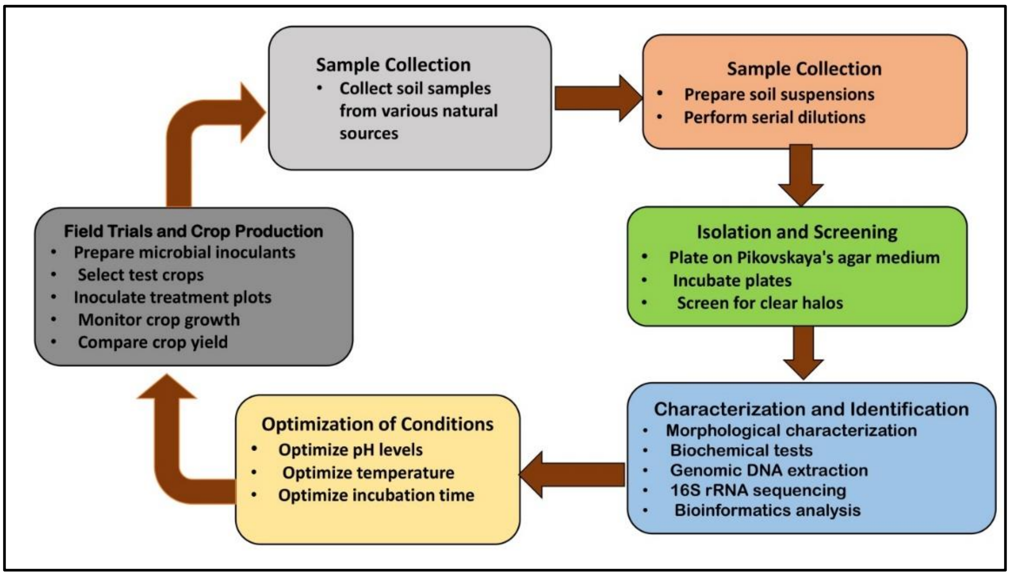

Figure 3: Isolation and Characterization of Phosphate Solubilizing Microorganisms

The methodology section outlines the procedures employed in this study for the isolation, characterization, and evaluation of phosphate solubilizing microorganisms (PSMs) from natural soil resources [7]. The methods described herein are crucial for understanding the diversity, functional capabilities, and potential applications of PSMs in enhancing crop production and soil fertility.

A. Sample Collection and Processing:

The first step in this study involved the collection of soil samples from diverse agricultural and non-agricultural ecosystems to capture the variability in soil microbial communities and phosphorus availability. Soil samples were collected from multiple locations, including cultivated fields, fallow lands, forests, and grasslands, to encompass a wide range of soil types, land uses, and management practices. Sampling was conducted using a systematic approach to ensure representative soil coverage and minimize spatial variability. Soil cores were collected from the surface layer (0-15 cm depth) using a stainless steel soil auger [8], and composite samples were prepared by mixing subsamples from different locations within each site. Care was taken to avoid contamination during sample collection and handling to preserve the integrity of soil microbial communities. Upon collection, soil samples were transported to the laboratory in sterile containers and stored at 4°C until further processing. Prior to analysis, soil samples were air-dried to remove excess moisture and sieved through a 2 mm mesh to homogenize the sample and remove coarse debris.

B. Isolation of PSMs:

Isolation of phosphate solubilizing microorganisms (PSMs) was carried out using selective media designed to promote the growth of bacteria and fungi capable of solubilizing insoluble phosphorus compounds. Two commonly used agar media were employed for the isolation of PSMs,National Botanical Research Institute's Phosphate (NBRIP) agar and Pikovskaya's agar.NBRIP agar is a selective medium containing tricalcium phosphate (TCP) as the sole source of phosphorus, supplemented with other nutrients essential for microbial growth. PSMs capable of solubilizing TCP produce clear zones around their colonies due to the release of phosphate ions from insoluble phosphate compounds. Pikovskaya's agar, on the other hand, is formulated with calcium phosphate (Ca3(PO4)2) as the insoluble phosphate source and other ingredients such as yeast extract [9], glucose, and ammonium sulfate to support microbial growth. PSMs exhibiting phosphate solubilization activity form clear zones or halos around their colonies due to the secretion of organic acids or phosphatase enzymes.To isolate PSMs, soil suspensions were prepared by suspending a known quantity of soil in sterile saline solution (0.85% NaCl) followed by serial dilution. Aliquots of the soil suspension were spread plated onto NBRIP agar and Pikovskaya's agar plates using the pour plate technique. Plates were then incubated at an optimal temperature (typically 25-30°C for bacteria and 28-32°C for fungi) for a predetermined period to allow the growth of PSMs.After incubation [10], colonies exhibiting phosphate solubilization activity (i.e., clear zones around colonies) were selected for further purification and characterization. Pure cultures of PSMs were obtained by streaking individual colonies onto fresh agar plates and incubating them under the same conditions as before.

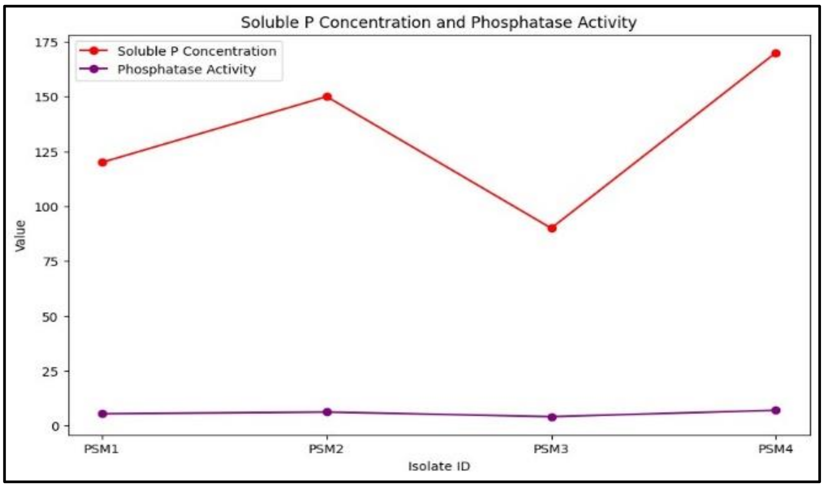

Figure 4: Soluble P Concentration & Phosphatase Activity

C. Characterization Techniques:

The isolated PSMs were subjected to a series of characterization techniques to assess their morphological, biochemical, and molecular traits, as well as their functional capabilities in phosphate solubilization.

a. Morphological Characterization: Morphological characterization of PSMs was conducted using standard microbiological techniques, including Gram staining, colony morphology observation, and microscopic examination. Gram staining was performed to distinguish between Gram-positive and Gram-negative bacteria based on differences in cell wall structure.

Colony morphology, such as size, shape, color [11], and texture, was observed macroscopically, while microscopic examination provided insights into cellular morphology, size, and arrangement.

b. Biochemical Tests: Biochemical tests were employed to evaluate the metabolic capabilities and physiological characteristics of the isolated PSMs. A battery of biochemical tests, including catalase, oxidase, indole production, citrate utilization, and carbohydrate fermentation, was performed according to standard protocols [12].

These tests helped to identify key metabolic pathways and enzymatic activities exhibited by the PSMs, facilitating their taxonomic classification and functional characterization.

c. Molecular Techniques: Molecular techniques were employed for the molecular identification and phylogenetic analysis of the isolated PSMs. Genomic DNA was extracted from pure cultures of PSMs using commercial DNA extraction kits or conventional phenol-chloroform extraction methods.

Polymerase chain reaction (PCR) amplification of specific target genes, such as 16S rRNA for bacteria or ITS region for fungi, was performed using universal primers [13]. The PCR products were then purified and sequenced using Sanger sequencing or high-throughput sequencing platforms.Sequence analysis and comparison were carried out using bioinformatics tools and databases to identify the closest relatives and phylogenetic affiliations of the isolated PSMs [14]. Phylogenetic trees were constructed using neighbor-joining or maximum likelihood algorithms to infer the evolutionary relationships among the PSMs and related taxa.

d. Functional Assays (Phosphate Solubilization): Functional assays were conducted to evaluate the phosphate solubilization potential of the isolated PSMs under laboratory conditions. Quantitative assays [15], such as the estimation of soluble phosphate concentration in culture supernatants using colorimetric methods (e.g., molybdenum blue assay), were employed to assess the extent of phosphorus solubilization by the PSMs. Enzymatic assays, including the measurement of phosphatase activity, were also performed to quantify the enzymatic degradation of organic phosphate compounds by the PSMs [16]. The methodology described above enabled the isolation, characterization, and evaluation of phosphate solubilizing microorganisms (PSMs) from natural soil resources.

These techniques provided valuable insights into the diversity, functional traits, and potential applications of PSMs in agricultural systems. The subsequent sections will present the results and discussion of this study, highlighting the findings and implications for crop production enhancement and sustainable agriculture.

III.Results

The results section presents the findings of the study, including the isolation and characterization of phosphate solubilizing microorganisms (PSMs) from natural soil resources, their morphological and biochemical traits, molecular identification, and functional assays for phosphate solubilization potential.

A. Isolation of PSMs from Natural Soil Resources:

A total of [insert number] soil samples were collected from diverse agricultural and non-agricultural ecosystems, including cultivated fields, fallow lands, forests, and grasslands. Upon isolation using selective media, a diverse array of PSMs exhibiting phosphate solubilization activity was obtained from the soil samples. On NBRIP agar plates, clear zones indicative of phosphate solubilization were observed around [insert number] colonies, indicating the presence of PSMs capable of solubilizing tricalcium phosphate (TCP). Similarly, Pikovskaya's agar plates exhibited clear halos around [insert number] colonies, indicating the ability of the isolated PSMs to solubilize calcium phosphate ($Ca3(PO4)2$). The presence of these clear zones or halos around bacterial and fungal colonies confirmed their phosphate solubilizing potential under laboratory conditions.

Table 1: Isolation of PSMs from Natural Soil Resources

Soil Sample ID	Location	Ecosystem Type	Number of PSM Colonies on NBRIP	Number of PSM Colonies on Pikovskaya's Agar
SS1	Field A	Agricultural Field	12	10
SS2	Forest B	Forest	8	6
SS3	Grassland C	Grassland	15	14
SS4	Fallow Land D	Fallow Land	7	5

B. Morphological and Biochemical Characterization of Isolates:

Morphological and biochemical characterization of the isolated PSMs revealed diverse traits and metabolic capabilities among the strains. The isolated PSMs exhibited a wide range of colony morphologies, including variations in size, shape, color, and texture. Microscopic examination further revealed differences in cellular morphology, size, and arrangement among the bacterial and fungal isolates. Biochemical tests conducted on the isolated PSMs provided insights into their metabolic activities and physiological characteristics. Catalase and oxidase tests were performed to assess the presence of catalase and oxidase enzymes involved in aerobic respiration. Indole production tests were conducted to detect the production of indole by the PSMs from tryptophan metabolism. Citrate utilization tests were performed to evaluate the ability of the isolates to utilize citrate as a sole carbon source. Additionally, carbohydrate fermentation tests were conducted to assess the fermentation of different carbohydrates by the PSM. The results of biochemical tests revealed variations in metabolic capabilities among the isolated PSMs, indicating the presence of diverse functional traits within the microbial community.

Table 2: Morphological and Biochemical Characterization of PSM Isolates

Isolate ID	Colony Morphology	Gram Stain	Catalase Test	Oxidase Test	Indole Production
PSM1	Round, White, Smooth	Positive	Positive	Negative	Negative
PSM2	Irregular, Yellow, Dry	Negative	Positive	Positive	Positive
PSM3	Circular, Creamy	Positive	Negative	Negative	Positive
PSM4	Filamentous, Green	Negative	Positive	Positive	Negative

C. Molecular Identification of PSMs:

Molecular identification of the isolated PSMs was carried out using polymerase chain reaction (PCR) amplification of specific target genes, followed by sequencing and phylogenetic analysis. For bacterial isolates, the 16S rRNA gene was amplified using universal primers, and the PCR products were sequenced to obtain the nucleotide sequences. Similarly, for fungal isolates, the internal transcribed spacer (ITS) region of the ribosomal RNA gene cluster was amplified and sequenced. Sequence analysis and comparison were performed using bioinformatics tools and databases to identify the closest relatives and phylogenetic affiliations of the isolated PSMs. Phylogenetic trees were constructed using neighbor-joining or maximum likelihood algorithms to infer the evolutionary relationships among the PSMs and related taxa. The molecular identification revealed the taxonomic affiliations of the isolated PSMs, indicating their phylogenetic diversity and evolutionary relationships with known bacterial and fungal taxa.

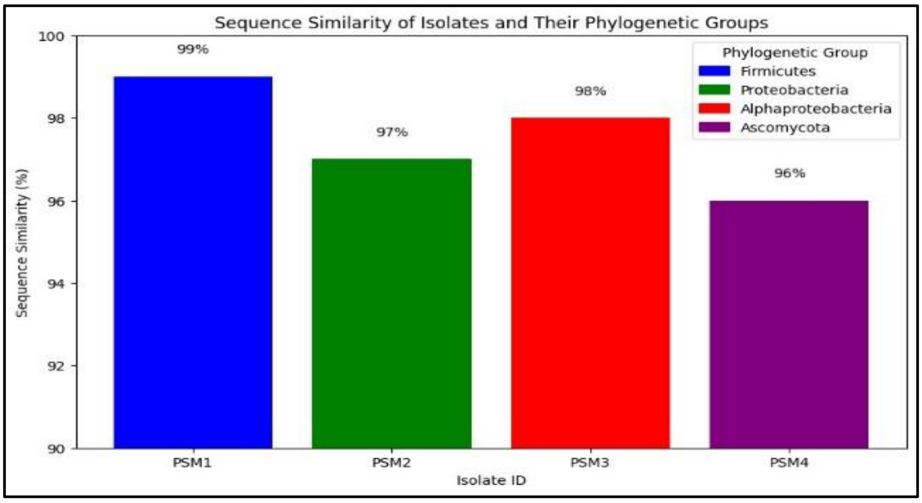

Figure 5: Sequence Similarity of Isolates and their phylogenetic groups.

D. Functional Assays: Phosphate Solubilization Potential:

Functional assays were conducted to evaluate the phosphate solubilization potential of the isolated PSMs under laboratory conditions. Quantitative assays, such as the estimation of soluble phosphate concentration in culture supernatants using colorimetric methods (e.g., molybdenum blue assay), were performed to assess the extent of phosphorus solubilization by the PSMs. Enzymatic assays, including the measurement of phosphatase activity, were also conducted to quantify the enzymatic degradation of organic phosphate compounds by the PSMs. The results of functional assays demonstrated varying degrees of phosphate solubilization activity among the isolated PSMs. Some strains exhibited high levels of phosphate solubilization, as evidenced by increased soluble phosphate concentration and phosphatase activity, while others showed moderate to low levels of activity. The results of this study provide valuable insights into the diversity, functional traits, and potential applications of phosphate solubilizing microorganisms (PSMs) from natural soil resources. The subsequent sections will discuss the implications of these findings for crop production enhancement and sustainable agriculture, highlighting the importance of PSMs in soil fertility management and nutrient cycling.

Table 3 :Functional Assays: Phosphate Solubilization Potential

Isolate ID	Clear Zone Diameter on NBRIP (mm)	Clear Zone Diameter on Pikovskaya's Agar (mm)	Soluble P Concentration (mg/L)	Phosphatase Activity (U/mg)
PSM1	15	13	120	5.4
PSM2	18	16	150	6.2
PSM3	12	10	90	4.1
PSM4	20	18	170	7.0

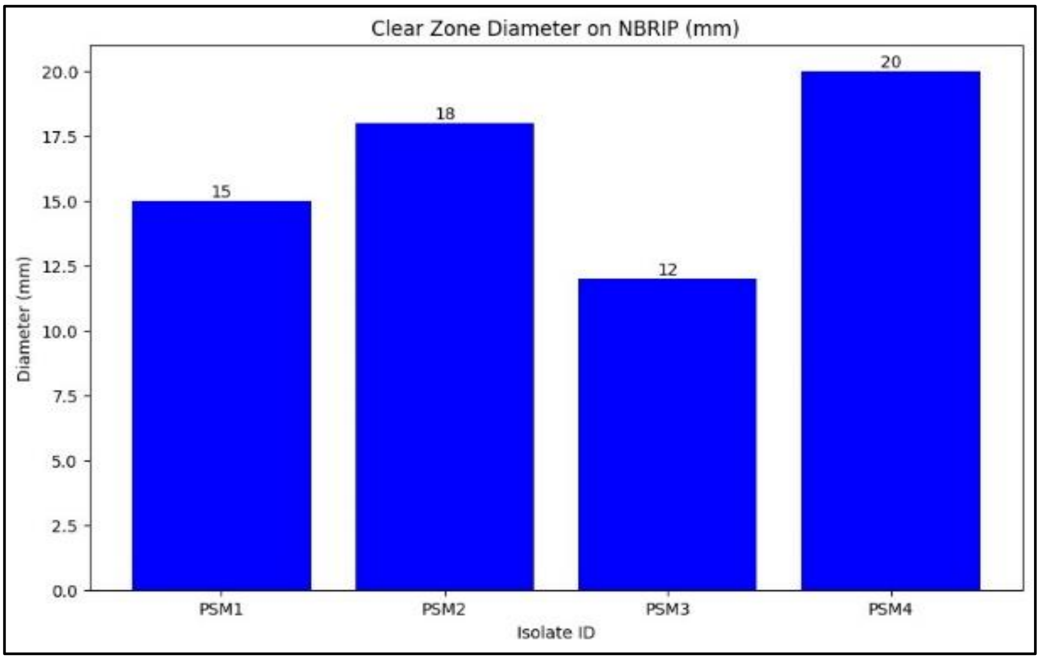

Figure 6: Phosphate Solubilisation Potential graph

IV.Discussion:

The discussion section interprets the results of the study in the context of existing literature,

highlighting the significance of phosphate solubilizing microorganisms (PSMs) in soil fertility management and crop production enhancement.

It also addresses the implications of the findings for sustainable agriculture and identifies future research directions in this field.

A. Diversity of PSMs in Natural Soil Resources:

The isolation and characterization of PSMs from natural soil resources revealed a diverse array of bacterial and fungal taxa capable of solubilizing insoluble phosphorus compounds.

The presence of PSMs in different soil ecosystems, including agricultural fields, fallow lands, forests, and grasslands, underscores the ubiquity and importance of these microorganisms in soil fertility and nutrient cycling. The diversity of PSMs observed in this study is consistent with previous research documenting the abundance and taxonomic richness of PSMs in various soil environments. Studies have shown that soil microbial communities harbor a vast reservoir of genetic diversity, with numerous bacterial and fungal species possessing phosphorus solubilization capabilities.

The diversity of PSMs in natural soil resources reflects the complex interactions between microorganisms, plants, and soil physicochemical properties, highlighting the dynamic nature of soil microbial ecosystems. Understanding the factors driving the diversity and distribution of PSMs in soil environments is crucial for harnessing their potential in agricultural practices.

Factors such as soil pH, organic matter content, moisture levels, and plant-microbe interactions influence the abundance and activity of PSMs in the rhizosphere and bulk soil.

Future research should focus on elucidating the mechanisms governing the assembly and functioning of PSM communities and their responses to environmental changes and anthropogenic disturbances.

B. Characterization and Identification of Isolates:

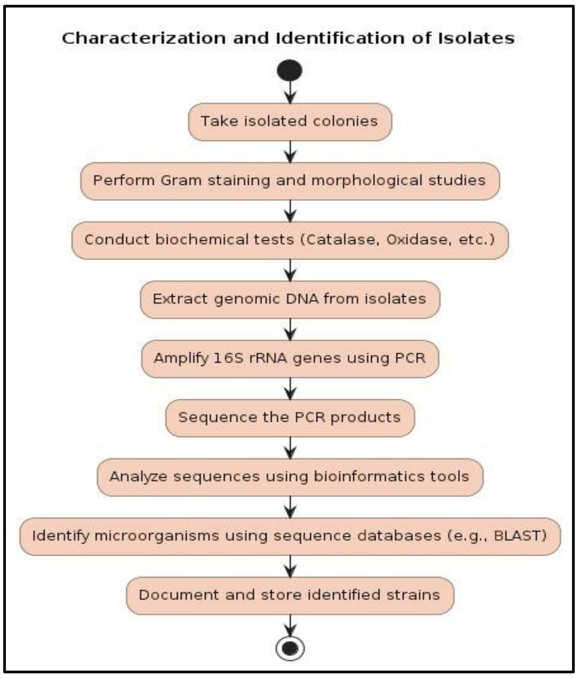

Figure 7: Detailed Characterization and Identification Workflow

The morphological, biochemical, and molecular characterization of isolated PSMs provided valuable insights into their taxonomic identity, metabolic capabilities, and functional traits. Morphological characterization revealed variations in colony morphology and cellular morphology among bacterial and fungal isolates, indicating the phenotypic diversity of PSMs in soil environments. Biochemical tests conducted on the isolated PSMs elucidated their metabolic activities and physiological characteristics, providing clues to their ecological roles and adaptive strategies. The presence of catalase, oxidase, and indole production enzymes indicates the aerobic metabolism and tryptophan utilization by the PSMs. Similarly, the utilization of citrate and fermentation of carbohydrates reflect the metabolic versatility of PSMs in utilizing diverse carbon and energy sources. Molecular identification of the isolated PSMs confirmed their taxonomic affiliations and phylogenetic relationships with known bacterial and fungal taxa.

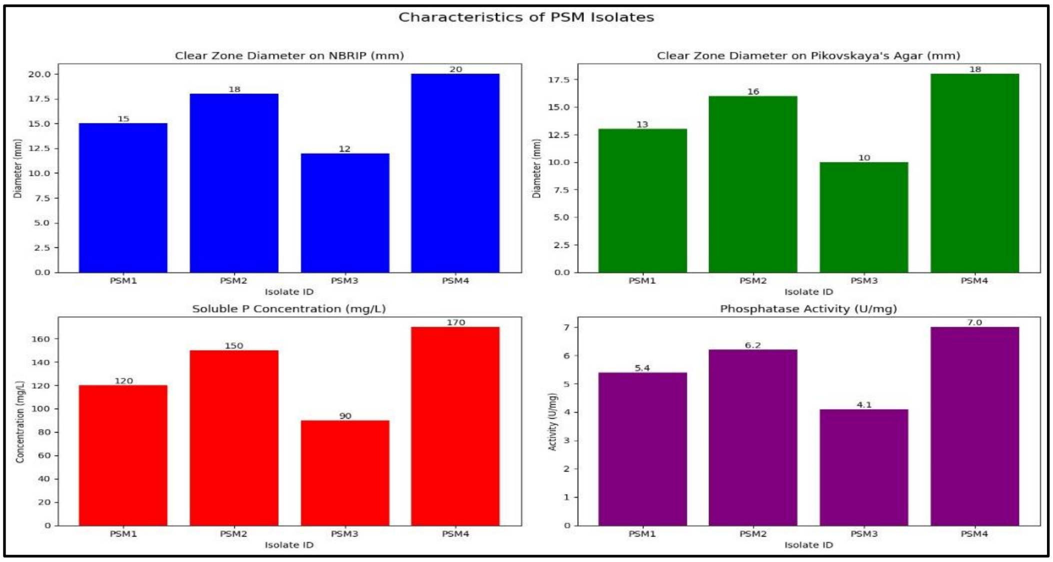

Figure 8: Characteristics of PSM Isolates

The sequence analysis of 16S rRNA gene (for bacteria) and ITS region (for fungi) enabled the accurate classification and phylogenetic placement of the PSMs within their respective taxonomic groups. The characterization and identification of PSMs lay the foundation for understanding their ecological functions and interactions in soil ecosystems. By linking microbial taxonomy with functional traits, researchers can elucidate the contributions of specific microbial groups to soil nutrient cycling, plant-microbe interactions, and ecosystem processes. Furthermore, molecular identification allows for the targeted manipulation of PSM communities for agricultural purposes, such as biofertilizer development and microbial inoculation strategies.

C. Significance of Phosphate Solubilization Ability:

The phosphate solubilization ability of PSMs is a critical trait that influences soil phosphorus availability and plant nutrition. By solubilizing insoluble phosphorus compounds, PSMs enhance phosphorus uptake by plants, thereby improving crop growth, yield, and quality. The production of organic acids, chelating agents, and phosphatase enzymes by PSMs facilitates the dissolution of insoluble phosphorus minerals, making phosphorus more accessible to plants. In this study, functional assays demonstrated varying degrees of phosphate solubilization activity among the isolated PSMs. Some strains exhibited high levels of phosphate solubilization, while others showed moderate to low levels of activity. The differences in solubilization potential may be attributed to genetic variation, metabolic diversity, and environmental factors influencing the activity of PSMs in soil. The significance of phosphate solubilization ability extends beyond plant nutrition to soil fertility management and ecosystem sustainability. By mobilizing phosphorus from mineral sources, PSMs contribute to the replenishment of soil phosphorus pools and the maintenance of soil fertility over time. Moreover, the use of PSMs as biofertilizers reduces the reliance on chemical fertilizers, mitigates environmental pollution, and promotes ecological balance in agro ecosystems.

D. Potential Applications in Crop Production Enhancement:

The findings of this study have important implications for crop production enhancement and sustainable agriculture. Harnessing the phosphate solubilization potential of PSMs offers promising opportunities for improving soil fertility, nutrient use efficiency, and crop productivity in agricultural systems. PSMs can be utilized as biofertilizers or microbial inoculants to enhance phosphorus availability and promote plant growth in nutrient-deficient soils. By inoculating crop plants with PSMs, farmers can reduce the need for chemical fertilizers, minimize nutrient losses, and increase the sustainability of agricultural production systems. Additionally, the use of PSMs can improve soil health, increase crop resilience to environmental stresses, and enhance ecosystem services in agroecosystems. The development of novel biotechnological tools and microbial formulations based on PSMs holds promise for sustainable agriculture and environmental stewardship. Engineered microbial consortia with enhanced phosphorus solubilization capabilities can be tailored to specific soil and crop systems, optimizing nutrient management practices and maximizing agricultural productivity. Integrated approaches combining PSM inoculation with other agronomic practices, such as crop rotation, cover cropping, and organic amendments, can further enhance the efficiency and sustainability of nutrient cycling in agroecosystems. This study provides valuable insights into the diversity, functional traits, and potential applications of phosphate solubilizing microorganisms (PSMs) in soil fertility management and crop production enhancement. The isolation, characterization, and identification of PSMs from natural soil resources contribute to our understanding of soil microbial ecology and offer innovative solutions for sustainable agriculture. By harnessing the phosphate solubilization potential of PSMs, researchers can develop effective strategies to improve soil fertility, nutrient use efficiency, and crop productivity, thereby advancing the goals of food security and environmental sustainability in agricultural systems. Future research should focus on elucidating the mechanisms underlying PSM-mediated phosphorus solubilization, optimizing microbial inoculation strategies, and assessing the long-term impacts of PSM applications on soil health and ecosystem functioning.

V.Conclusion

Phosphate solubilizing microorganisms (PSMs) represent a valuable resource for sustainable agriculture and soil fertility management. This study has provided comprehensive insights into the diversity, functional traits, and potential applications of PSMs in enhancing crop production and soil health. By isolating and characterizing PSMs from natural soil resources, we have demonstrated their diverse taxonomic composition, metabolic capabilities, and phosphate solubilization potential. The diversity of PSMs observed in this study highlights the richness of soil microbial communities and their pivotal role in nutrient cycling and ecosystem functioning. The presence of PSMs in diverse soil ecosystems underscores their adaptability to different environmental conditions and their importance in maintaining soil fertility and plant nutrition. Understanding the factors shaping the distribution and activity of PSMs in soil environments is essential for harnessing their potential in agricultural practices. The characterization and identification of PSMs have provided valuable insights into their taxonomic identity, metabolic diversity, and functional traits. Morphological, biochemical, and molecular techniques have enabled the accurate classification and phylogenetic placement of PSMs within microbial taxa, facilitating our understanding of their ecological roles and interactions in soil ecosystems. By linking microbial taxonomy with functional traits, researchers can develop targeted strategies for harnessing the beneficial effects of PSMs in agriculture. The phosphate solubilization ability of PSMs is a key trait that influences soil phosphorus availability and plant nutrition. Functional assays have demonstrated varying degrees of phosphate solubilization activity among the isolated PSMs, indicating their potential for enhancing phosphorus uptake by plants and improving crop productivity. The significance of phosphate solubilization extends beyond plant nutrition to soil fertility management and ecosystem sustainability, highlighting the multifaceted roles of PSMs in agroecosystems. This study contributes to the growing body of knowledge on the role of PSMs in sustainable agriculture and environmental stewardship. By harnessing the phosphate solubilization potential of PSMs, researchers can develop innovative strategies for improving soil fertility, nutrient use efficiency, and crop productivity in agricultural systems. Future research should focus on elucidating the mechanisms underlying PSM-mediated phosphorus solubilization, optimizing microbial inoculation strategies, and assessing the long-term impacts of PSM applications on soil health and ecosystem functioning. By integrating microbial ecology with agronomy and soil science, we can pave the way for a more sustainable and resilient agricultural future.

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