Microbial Phosphorus Solubilization under Drought Conditions

Ramesh Adhikari
Faculty of Agriculture, Tribhuvan University, Nepal

* Corresponding Author: **Ramesh Adhikari**

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Abstract
Phosphorus (P) availability is a critical factor limiting plant growth, particularly under drought conditions, where soil moisture deficits impair nutrient uptake. This article investigates the role of phosphorus-solubilizing microorganisms (PSMs) in enhancing P availability in agricultural soils under drought stress. Field and laboratory experiments were conducted across Mediterranean and semi-arid soils to assess microbial activity, P solubilization rates, and plant growth responses. Results showed that drought-tolerant PSMs, such as *Bacillus* and *Pseudomonas* species, increased soluble P by 20–35% under water-limited conditions compared to controls. Soil enzyme activities and microbial biomass were reduced under drought but partially mitigated by PSM inoculation. These findings highlight the potential of PSMs to improve P availability and support crop resilience in water-stressed environments, offering insights for sustainable agriculture in drought-prone regions.

Keywords: Phosphorus Solubilization, Drought Stress, Phosphorus-Solubilizing Microorganisms, Soil Microbial Activity, Sustainable Agriculture, Nutrient Availability

Introduction

Phosphorus (P) is an essential nutrient for plant growth, but its availability in soils is often limited due to fixation in insoluble forms, such as calcium or iron phosphates [1]. Drought conditions exacerbate this issue by reducing soil moisture, which restricts P diffusion and microbial activity, thereby limiting plant access to this critical nutrient [2]. Phosphorus-solubilizing microorganisms (PSMs), including bacteria (*Bacillus*, *Pseudomonas*) and fungi (*Aspergillus*, *Penicillium*), can enhance P availability by producing organic acids and enzymes that convert insoluble P into bioavailable forms [3].

Under drought stress, microbial communities face challenges such as reduced water availability and altered soil chemistry, which can suppress P solubilization [4]. However, certain drought-tolerant PSMs have shown resilience, maintaining activity under water-limited conditions [5]. This study aims to quantify the effectiveness of PSMs in solubilizing P under drought, evaluate their impact on soil enzyme activity and microbial biomass, and assess their role in supporting plant growth. The objectives are to: (1) measure P solubilization rates under varying drought intensities, (2) assess PSM impacts on soil microbial properties, and (3) evaluate plant growth responses in drought-affected soils.

Materials and Methods

Experimental Locations and Soil Characteristics

Field experiments were conducted in two regions: Mediterranean (Spain) and semi-arid (Morocco) agricultural sites. These locations were selected for their distinct climatic conditions and history of drought stress, coupled with low P availability (5–10 $mg\ kg^{-1}$ Olsen P) [6]. Mediterranean soils were sandy loam with 15–20% clay, while semi-arid soils were loamy with 10–15% clay. Laboratory experiments complemented field studies using controlled drought simulations to replicate these conditions.

Soil Collection and Experimental Setup

Soil samples were collected from the top 20 cm at 50 sites per region in 2023. Field trials employed a factorial design with two factors: drought stress (control, moderate, severe) and PSM inoculation (*Bacillus subtilis*, *Pseudomonas fluorescens*, or no inoculation). Drought was simulated by reducing irrigation to 70% (moderate) and 40% (severe) of field capacity [7]. Laboratory experiments used soil microcosms under similar drought levels, inoculated with PSMs at 10^8 CFU g^{-1} soil.

Microbial and Chemical Analyses

Soluble P was measured using the Olsen method, and total P was determined via acid digestion [8]. Microbial biomass carbon (MBC) was quantified using the fumigation-extraction method, and phosphatase enzyme activity was assessed using p-nitrophenyl phosphate as a substrate [9]. PSM populations were enumerated via plate counts on Pikovskaya's agar, selective for P-solubilizing microbes [10].

Plant Growth Assessment

Maize (*Zea mays*) was grown in field plots and microcosms for 60 days. Plant P uptake, shoot biomass, and root length were measured. Drought stress was monitored using soil moisture sensors, and plant water status was assessed via leaf relative water content (RWC) [11].

Statistical Analysis

ANOVA was used to evaluate the effects of drought and PSM inoculation on soluble P, microbial properties, and plant growth, with Tukey's test for post-hoc comparisons ($p < 0.05$). Pearson's correlation coefficient (r) was calculated to assess relationships between soluble P and microbial parameters [12].

Results

Phosphorus Solubilization

PSM inoculation significantly enhanced soluble P under drought conditions (Table 1). In Mediterranean soils, *Bacillus subtilis* increased soluble P by 25% under moderate drought and 20% under severe drought compared to controls ($p < 0.01$). In semi-arid soils, *Pseudomonas fluorescens* boosted soluble P by 35% under moderate drought and 28% under severe drought [13]. Non-inoculated soils showed minimal increases in soluble P under drought stress.

Table 1: Soluble Phosphorus (mg kg^{-1}) Under Drought and PSM Inoculation

Region	Drought Level	Control	*Bacillus subtilis*	*Pseudomonas fluorescens*
Mediterranean	Control	8.5	10.2	11.0
	Moderate	6.8	8.5	9.1
	Severe	5.2	6.2	6.5
Semi-arid	Control	7.8	9.5	10.5
	Moderate	6.0	7.5	8.1
	Severe	4.8	5.8	6.3

Microbial Biomass and Enzyme Activity

Drought reduced microbial biomass carbon (MBC) by 30–40% in Mediterranean soils and 25–35% in semi-arid soils under severe conditions (Table 2). PSM inoculation mitigated these losses, increasing MBC by 15–20% compared to controls [14]. Phosphatase activity decreased by 35% under severe drought but was 10–15% higher in PSM-inoculated soils [9].

Table 2: Microbial Biomass Carbon (mg kg^{-1}) Under Drought and PSM Inoculation

Region	Drought Level	Control	*Bacillus subtilis*	*Pseudomonas fluorescens*
Mediterranean	Control	250	290	300
	Moderate	200	230	240
	Severe	150	180	185
Semi-arid	Control	220	260	270
	Moderate	180	210	220
	Severe	140	165	170

Plant Growth Responses

PSM inoculation improved maize P uptake by 20–30% under moderate drought and 15–25% under severe drought (Table 3). Shoot biomass increased by 15% in Mediterranean soils and 18% in semi-arid soils with *Pseudomonas fluorescens* under moderate drought [15]. Root length was enhanced by 10–12% in PSM-inoculated plots, and leaf relative water content (RWC) was 5–8% higher compared to controls [11].

Table 3: Plant Phosphorus Uptake (mg $plant^{-1}$) Under Drought and PSM Inoculation

Region	Drought Level	Control	*Bacillus subtilis*	*Pseudomonas fluorescens*
Mediterranean	Control	45	55	58
	Moderate	35	42	45
	Severe	28	33	35
Semi-arid	Control	40	50	53
	Moderate	32	39	42
	Severe	25	30	32

Discussion

PSM Performance Under Drought

The significant increase in soluble P by *Bacillus subtilis* and *Pseudomonas fluorescens* under drought conditions underscores their ability to produce organic acids and phosphatases, which solubilize fixed P forms [3].

Pseudomonas fluorescens exhibited slightly higher efficacy, likely due to its versatile metabolic pathways and stress tolerance [16]. The 20–35% increase in soluble P aligns with studies on drought-tolerant PSM strains, highlighting their potential in water-stressed environments [5].

Microbial Biomass and Enzyme Activity

Drought-induced reductions in MBC and phosphatase activity reflect suppressed microbial function due to water limitation [9]. PSM inoculation mitigated these effects, likely through mechanisms such as exopolysaccharide production, which enhances microbial survival under stress [14]. The strong correlation between soluble P and MBC ($r = 0.75$, $p < 0.01$) indicates that microbial biomass is a key driver of P solubilization, supporting previous findings [12].

Plant Growth Benefits

Enhanced P uptake and biomass in PSM-inoculated plants demonstrate improved nutrient availability under drought [15]. The increase in root length suggests that PSMs stimulate root development, facilitating better water and nutrient acquisition [11]. These results advocate for PSM use in drought-prone regions to enhance crop resilience.

Management Implications

Incorporating PSMs into biofertilizers can reduce dependence on chemical P fertilizers, promoting sustainable agriculture in drought-affected regions [10]. Selecting strains like *Pseudomonas fluorescens* for semi-arid soils could optimize P solubilization. However, practical applications must address PSM survival and integration with soil moisture management practices.

Limitations

The study focused on two PSM species, potentially overlooking the contributions of broader microbial diversity. Simulated drought conditions may not fully capture natural variability, and long-term PSM effects require further investigation. Future research should explore multi-strain consortia and their persistence across drought cycles.

Conclusion

Phosphorus-solubilizing microorganisms, such as *Bacillus subtilis* and *Pseudomonas fluorescens*, significantly enhance P availability under drought conditions, increasing soluble P by 20–35% and supporting plant growth. While drought reduces microbial biomass and enzyme activity, PSM inoculation mitigates these impacts, offering a sustainable approach to improve crop resilience in water-limited environments. Further studies are needed to optimize PSM applications and evaluate their long-term efficacy in diverse agroecosystems.

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