Harnessing Stress-Tolerant Soil Microbes: Nitrogen-Fixing and Phosphate-Solubilizing Bacteria as Bioinoculants for Wheat in Waterlogged and Drought-Affected Soils

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Abstract

Wheat (*Triticum aestivum* L.) production faces significant challenges from waterlogging and drought stress, which severely impact global food security. These abiotic stresses disrupt plant physiological processes, alter nutrient availability, and reduce crop yields. This comprehensive review examines the potential of stress-tolerant nitrogen-fixing bacteria (NFB) and phosphate-solubilizing bacteria (PSB) as bioinoculants to enhance wheat resilience in water-stressed environments. We analyze the fundamental mechanisms of biological nitrogen fixation and phosphate solubilization and explore the adaptations that enable certain bacterial strains to maintain these functions under osmotic stress and oxygen deprivation. These adaptations include osmolyte accumulation, exopolysaccharide production, biofilm formation, ACC deaminase activity, and alternative respiration pathways. The review synthesizes evidence on how these stress-tolerant microbes improve wheat growth parameters, nutrient acquisition, and physiological responses under waterlogging and drought conditions. We further examine the synergistic effects observed when NFB and PSB are co-inoculated, highlighting their complementary roles in enhancing nutrient availability and stress tolerance. Despite promising results, formulation stability, field application consistency, and strain compatibility remain. Future research should focus on advanced screening methods for stress-tolerant strains, optimized formulation technologies, and field validation across diverse agroecological zones. This review provides a foundation for developing effective microbial strategies to sustainably enhance wheat productivity in the face of increasing climate variability and water-related stresses.

Keywords: Wheat, Nitrogen-fixing bacteria, Phosphate-solubilizing bacteria, Waterlogging, Drought stress, Bioinoculants, Stress tolerance

1. Introduction

Wheat (*Triticum aestivum* L.) stands as a cornerstone of global food security, providing approximately 20% of the total caloric and protein intake for the world's population (1). Its cultivation spans vast areas worldwide, making it the third most cultivated cereal crop globally. However, achieving and sustaining high yields necessary to meet the demands of a growing population is increasingly challenged by various environmental constraints, particularly abiotic stresses exacerbated by climate change (2-4). Among these, waterlogging and drought represent two major limiting factors that significantly curtail wheat productivity in numerous agricultural regions.

Waterlogging, characterized by excess water saturating the soil profile, affects an estimated 10–15 million hectares of wheat cultivation annually, leading to substantial yield losses ranging from 20% to 50% (1). This condition arises from excessive precipitation, poor soil drainage, or inadequate irrigation management, creating hypoxic or anoxic conditions in the root zone (1, 2). The lack of oxygen severely impairs root respiration, nutrient and water uptake, and overall plant growth, often leading to physiological damage such as chlorosis, senescence, and increased susceptibility to diseases (1). Conversely, drought stress, marked by insufficient water availability, poses an equally significant threat to wheat production globally (5). Water scarcity limits essential physiological processes, including photosynthesis and nutrient transport, resulting in stunted growth, reduced biomass accumulation, and ultimately, diminished grain yield.

The detrimental impacts of both waterlogging and drought are often mediated through complex physiological and biochemical responses within the plant. Waterlogging, for instance, triggers the excessive production of ethylene, a plant hormone that, under stress conditions, can accelerate senescence and inhibit growth (2). Both stresses also induce oxidative stress through the overproduction of reactive oxygen species (ROS), which damage cellular components like membranes, proteins, and nucleic acids (1). Furthermore, these stresses severely impact nutrient availability and uptake. Waterlogging alters soil redox potential and pH, affecting the solubility and availability of essential nutrients like nitrogen (N) and phosphorus (P) (1), while drought limits nutrient transport from the soil to the plant roots.

Addressing these challenges requires sustainable agricultural strategies that enhance crop resilience while minimizing reliance on synthetic inputs. The use of beneficial soil microorganisms, particularly plant growth-promoting bacteria (PGPB), as bioinoculants has emerged as a promising eco-friendly approach (2, 6, 7). Among PGPB, nitrogen-fixing bacteria (NFB) and phosphate-solubilizing bacteria (PSB) are of particular interest for cereal crops like wheat. NFB convert atmospheric nitrogen (N2) into ammonia, a form usable by plants, thereby reducing the need for synthetic N fertilizers (6, 8). PSB enhance the availability of phosphorus, a critical nutrient often present in insoluble forms in the soil, by solubilizing mineral phosphates or mineralizing organic P sources (6, 9, 10)

However, the efficacy of conventional bioinoculants can be limited under stressful environmental conditions. Therefore, harnessing stress-tolerant microbial strains, particularly NFB and PSB adapted to survive and function under drought and waterlogging, is crucial for developing effective bioinoculant strategies for challenging environments (5). These resilient microbes possess specific mechanisms to cope with osmotic stress (drought) and oxygen deprivation (waterlogging), such as the production of osmoprotectants, exopolysaccharides (EPS), biofilm formation, and enzymes like ACC deaminase that mitigate ethylene stress under waterlogging (2, 5) *(Figure 1)*.

This review aims to synthesize the current understanding of stress-tolerant NFB and PSB as potential bioinoculants for enhancing wheat resilience and productivity in soils affected by waterlogging and drought. We will delve into the mechanisms employed by these bacteria for nitrogen fixation and phosphate solubilization, explore their specific adaptations to water stress (both excess and deficit), and examine their beneficial effects on wheat growth under these challenging conditions. Furthermore, we will discuss the potential for synergistic interactions when NFB and PSB are co-inoculated, address the challenges associated with bioinoculant formulation and field application, and highlight future research directions for optimizing the use of these beneficial microbes in sustainable wheat production systems facing water-related stresses.

2. Mechanisms of Nitrogen Fixation and Phosphate Solubilization by Soil Bacteria

The capacity of certain soil bacteria to enhance plant nutrient acquisition, particularly nitrogen (N) and phosphorus (P), is central to their role as effective bioinoculants. Nitrogen fixation and phosphate solubilization are two key processes mediated by distinct groups of plant growth-promoting bacteria (PGPB) that significantly contribute to plant nutrition and growth, especially in nutrient-limited or stressed environments.

2.1 Nitrogen Fixation

Biological nitrogen fixation (BNF) is the process by which atmospheric nitrogen gas (N2), which is largely inert and unavailable to plants, is converted into ammonia (NH3), a form readily assimilated by plants (6). This conversion is exclusively carried out by prokaryotic microorganisms known as diazotrophs, which possess the nitrogenase enzyme complex responsible for breaking the strong triple bond of N2 (11, 12). Diazotrophs can be symbiotic (e.g., *Rhizobium* in legume nodules) or free-living/associative (e.g., *Azotobacter*, *Azospirillum*, *Paenibacillus*) (6, 11). For non-leguminous crops like wheat, associative NFB, which colonize the rhizosphere or live as endophytes within plant tissues, are particularly relevant (8, 11).

The nitrogenase enzyme complex is highly sensitive to oxygen. Therefore, diazotrophs have evolved various strategies to protect this enzyme, including high respiration rates to consume oxygen, slime layer production (like EPS), or specialized cellular structures. The process is energetically demanding, requiring significant ATP input, which is often linked to the availability of carbon sources from the plant host or soil organic matter. Associative NFB like *Paenibacillus beijingensis* have demonstrated significant nitrogenase activity in association with wheat, contributing to the plant's nitrogen budget (11, 13).

2.2 Phosphate Solubilization

Phosphorus is an essential macronutrient for plant growth, involved in energy transfer (ATP), nucleic acid synthesis, and membrane structure. However, a large proportion of P in soils exists in insoluble forms, either as mineral phosphates (e.g., calcium phosphates in alkaline soils, iron and aluminum phosphates in acidic soils) or complexed within organic matter, rendering it unavailable for plant uptake (9, 11). Phosphate-solubilizing bacteria (PSB) play a crucial role in converting these insoluble P forms into soluble orthophosphate ions (H2PO4-, HPO42-) that plants can absorb (6, 10, 11).

The primary mechanism for mineral phosphate solubilization by PSB is the production and release of organic acids, such as gluconic acid, citric acid, oxalic acid, and lactic acid (10). These organic acids lower the soil pH in the immediate vicinity of the bacteria and chelate the metal cations (e.g., Ca2+, Fe3+, Al3+) bound to phosphate, thereby releasing soluble phosphate ions (10). Some PSB can also produce protons (H+) or inorganic acids (e.g., sulfuric acid from sulfur oxidation) that contribute to solubilization. Additionally, some bacteria release phosphatases and phytases, enzymes that mineralize organic phosphorus compounds, releasing inorganic phosphate (9). Genera like *Pseudomonas*, *Bacillus*, and *Paenibacillus* are well-known for their phosphate-solubilizing capabilities (6, 11, 14). For instance, *Paenibacillus* sp. B1 has been shown to effectively solubilize both inorganic and organic P sources (11, 15)

Understanding these fundamental mechanisms is essential for selecting and utilizing NFB and PSB effectively as bioinoculants, particularly when targeting strains that can maintain these functions under the challenging conditions imposed by drought and waterlogging.

3. Bacterial Adaptations to Drought and Waterlogging Stress

3.1 Drought Tolerance Mechanisms in Bioinoculants

Drought imposes severe osmotic stress and desiccation challenges on soil microorganisms, necessitating specialized adaptations for survival. Drought-tolerant bacteria employ multiple strategies to mitigate these stresses. One key mechanism is the accumulation of compatible solutes (osmolytes) such as proline, glycine betaine, and trehalose, which help maintain cellular turgor pressure and protect enzymes and membranes from denaturation (5). Additionally, many drought-resistant bacteria produce exopolysaccharides (EPS), forming a protective slime layer that retains moisture, enhances soil aggregation, and improves root adhesion (5). Biofilm formation further enhances survival by creating a hydrated microenvironment that shields bacteria from desiccation while facilitating nutrient exchange and intercellular communication. Stress-responsive proteins, including heat shock proteins (HSPs) and cold shock proteins (CSPs), also play a crucial role by preventing protein misfolding under adverse conditions. These adaptations not only ensure bacterial survival but also enhance their ability to support plant growth under drought stress.

3.2 Waterlogging Tolerance Mechanisms in Bioinoculants

Waterlogging leads to oxygen-deprived (hypoxic or anoxic) soil conditions, requiring bacteria to employ alternative metabolic strategies for survival. Facultative anaerobic bacteria can switch from aerobic respiration to anaerobic pathways, utilizing electron acceptors such as nitrate or sulfate (2). A critical adaptation in plant-growth-promoting bacteria (PGPB) is the production of ACC deaminase, which hydrolyzes the ethylene precursor 1-aminocyclopropane-1-carboxylate (ACC) into α-ketobutyrate and ammonia. This process reduces stress ethylene levels in plants while providing the bacteria with essential nitrogen and carbon sources (2). Additionally, bacteria in waterlogged soils must tolerate reduced redox conditions, including elevated levels of toxic compounds like sulfides and reduced metal ions (Fe^{2+}, Mn^{2+}) (1). These adaptations enable nitrogen-fixing and phosphate-solubilizing bacteria to remain functional under waterlogged conditions, thereby supporting plant resilience. The integration of such stress-tolerant microbial strains into bioinoculant formulations is essential for improving crop performance in fluctuating water regimes.

4. Effects of Stress-Tolerant NFB and PSB on Wheat under Drought and Waterlogging

4.1 Alleviation of Drought Stress Effects by Bioinoculants

The application of drought-tolerant nitrogen-fixing bacteria (NFB) and phosphate-solubilizing bacteria (PSB) as bioinoculants has demonstrated significant potential in mitigating water deficit stress in wheat. Studies involving osmotolerant strains such as *Providencia vermicola*, *Pantoea agglomerans*, *Pseudomonas knackmussi*, and *Bacillus* spp. have shown notable improvements in wheat growth under moderate (50% field capacity) and severe (25% field capacity) drought conditions (5). Key benefits include enhanced growth and biomass, where inoculated plants exhibit superior germination rates, increased shoot and root elongation, and greater fresh and dry weight accumulation compared to non-inoculated controls. This improvement is attributed to sustained nitrogen and phosphorus availability, as well as potential modifications in root architecture that facilitate better water uptake *(Figure 1)*.

Additionally, drought-tolerant bioinoculants help maintain physiological function by preserving chlorophyll content, ensuring continued photosynthetic activity despite water scarcity. They also mitigate oxidative stress by reducing malondialdehyde (MDA) levels—a marker of lipid peroxidation—and modulating proline accumulation, indicating lower cellular damage (5). Interestingly, while drought typically upregulates antioxidant enzymes (e.g., SOD, CAT, GPX), inoculated plants sometimes show reduced enzymatic activity, suggesting that microbial interactions alleviate stress before the plant's defense mechanisms are fully activated. Furthermore, effective root colonization, facilitated by exopolysaccharide (EPS) production and biofilm formation, ensures that bacterial benefits are delivered directly to the plant even under water-limited conditions.

4.2 Mitigation of Waterlogging Stress Effects by Bioinoculants

Waterlogging induces hypoxia and ethylene-mediated stress in wheat, but ACC deaminase-producing bioinoculants can counteract these effects. A primary benefit is the reduction of ethylene stress, where bacterial hydrolysis of the ethylene precursor (ACC) lowers ethylene levels by 2- to 4-fold, preventing symptoms such as leaf epinasty, chlorosis, and premature senescence (2). This mechanism not only supports plant survival but also maintains growth rates and reduces yield losses under waterlogged conditions.

Moreover, hypoxia-tolerant NFB and PSB strains help sustain nutrient uptake despite impaired root function in waterlogged soils. While waterlogging generally disrupts nitrogen and phosphorus absorption (1), microbial contributions via N fixation and P solubilization can partially compensate for these deficits. Although direct wheat-specific studies are limited, evidence from other crops suggests that ACC deaminase-active bacteria enhance root health and nutrient accessibility under flooding stress (2) *(Table 1)*.

By integrating drought and waterlogging tolerance mechanisms, these bioinoculants offer a dual-functional approach to enhancing wheat resilience in unpredictable climates. Their ability to improve nutrient availability while mitigating abiotic stress responses positions them as promising tools for sustainable agriculture in water-fluctuating environments.

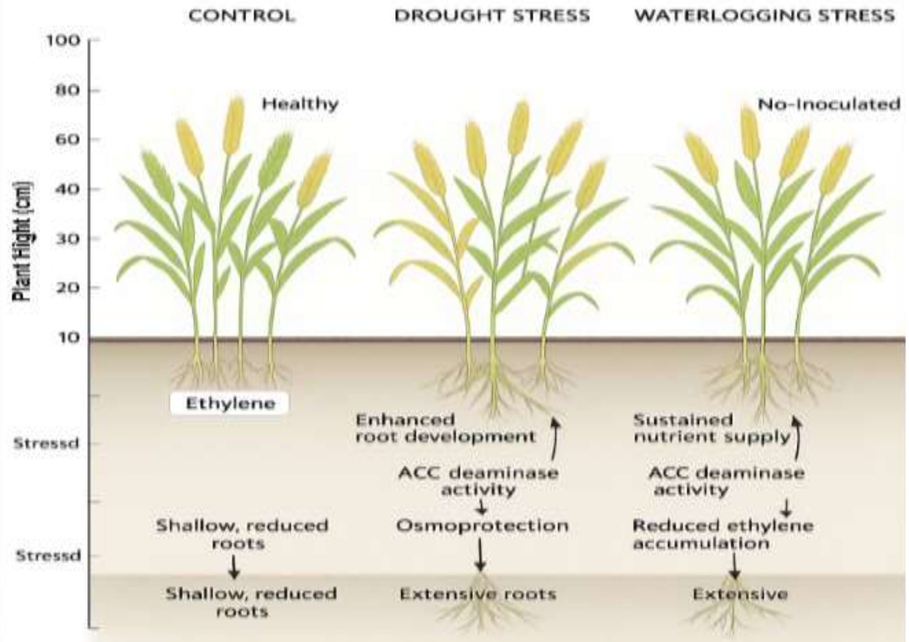

Figure 1. NFB/PSB inoculation enhances wheat stress tolerance under drought and waterlogging.

The figure compares wheat growth responses with and without stress-tolerant NFB/PSB inoculation under control, drought, and waterlogged conditions. Inoculated plants maintain better growth under both stresses: drought tolerance via improved nutrient/water uptake and osmoprotection, and waterlogging resilience through ACC deaminase-mediated ethylene reduction. (NFB=Nitrogen-Fixing Bacteria; PSB=Phosphate-Solubilizing Bacteria; ACC=1-Aminocyclopropane-1-carboxylic acid).

Table 1: Physiological and Biochemical Effects of Stress-Tolerant NFB/PSB Inoculation on Wheat under Drought and Waterlogging Stress

Stress Condition	**Parameter Measured**	**Effect of Inoculation**	**Key References**
Drought	Growth/Biomass	Increased germination, shoot/root length, biomass	(5)
	Chlorophyll Content	Maintained or increased	(5)
	Proline Content	Decreased (indicating less stress)	(5)
	MDA Content	Decreased (indicating less lipid peroxidation)	(5)
	Antioxidant Enzymes	Variable (sometimes decreased, indicating less need)	(5)
	Root Colonization	Enhanced	(5)
Waterlogging	Ethylene/ACC Levels	Decreased (due to ACC deaminase activity)	(2)
	Growth/Survival	Improved compared to non-inoculated under stress	(2)
	Chlorosis/Senescence	Reduced (due to lower ethylene stress)	(2)
	Nutrient Uptake	Potentially sustained despite stress	(1)

5. Synergistic Interactions and Co-inoculation

While single-strain inoculants of nitrogen-fixing bacteria (NFB) or phosphate-solubilizing bacteria (PSB) can provide significant benefits to plants, the combined application or co-inoculation of functionally distinct PGPB, particularly NFB and PSB, often leads to synergistic effects, resulting in greater improvements in plant growth, nutrient uptake, and stress tolerance than either strain applied alone. This synergy arises from the complementary roles these bacteria play in plant nutrition and potentially in stress mitigation.

5.1 Complementary Nutrient Provision

The most direct synergistic interaction stems from the enhanced availability of both nitrogen and phosphorus. PSB increase the pool of soluble phosphate available in the soil and rhizosphere. Phosphorus availability is often a limiting factor for the energetically expensive process of biological nitrogen fixation (11). By providing more available P, PSB can stimulate the activity of co-inoculated NFB, leading to increased nitrogen fixation rates.

Evidence for this synergy has been clearly demonstrated in wheat. Co-inoculation of wheat with the diazotroph *Paenibacillus beijingensis* BJ-18 and the P-solubilizer *Paenibacillus* sp. B1 resulted in significantly higher soil nitrogenase activity (+69%) and doubled the expression of the *nifH* gene (a marker for N-fixation) within plant tissues compared to inoculation with the N-fixer alone (11). This enhanced N-fixation was directly correlated with increased plant P content, highlighting the role of the PSB in facilitating BNF (11). Consequently, co-inoculated plants showed significantly greater increases in biomass and total N and P content compared to single inoculations (11). Similar synergistic effects on nutrient uptake and yield have been reported in other crops like chickpea when co-inoculated with NFB and PSB (16), *(see Figure 2)(Table 2)*.

5.2 Enhanced Stress Tolerance

Beyond nutrient synergy, co-inoculation can potentially enhance plant tolerance to abiotic stresses like drought and waterlogging through combined mechanisms. For instance, if one strain excels at producing EPS for drought protection while another produces ACC deaminase for waterlogging tolerance, their combined application could offer broader stress resilience. Furthermore, improved overall plant nutrition resulting from NFB-PSB synergy can inherently make the plant more robust and better equipped to withstand environmental stresses.

While specific studies focusing on co-inoculation of stress-tolerant NFB and PSB specifically for mitigating *both* drought and waterlogging in wheat are still emerging, the principle of combining complementary stress tolerance traits holds promise. Research on co-inoculating legumes with salt-tolerant bacteria and rhizobia points towards the effectiveness of combining stress tolerance with nutrient acquisition functions (17).

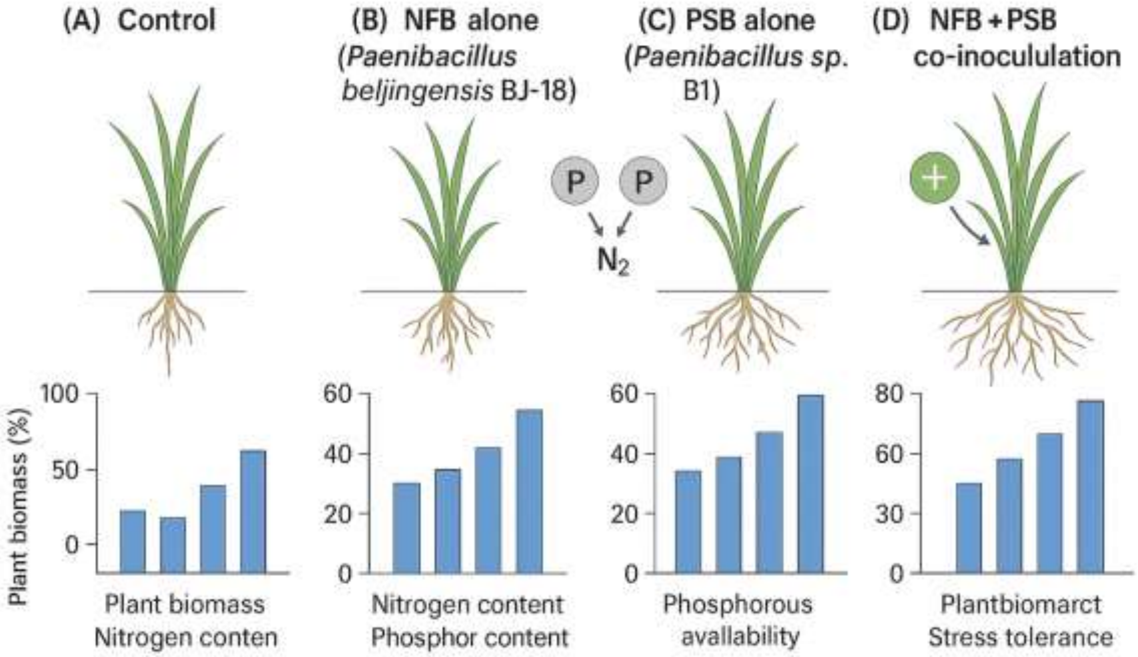

Figure 2: Synergistic effects of NFB (Paenibacillus beijingensis) and PSB (Paenibacillus sp. B1) co-inoculation on wheat under stress. (A) *Control (baseline),* ***(B)*** *NFB (28% shoot biomass ↑, 18× nifH↑),* ***(C)*** *PSB (25% biomass ↑),* ***(D)*** *NFB+PSB (49% biomass ↑, 158% nitrogenase ↑, 63× nifH↑). Sources: (8, 11, 13)*

Table 2: Examples of Synergistic Effects from Co-inoculation of Nitrogen-Fixing Bacteria (NFB) and Phosphate-Solubilizing Bacteria (PSB)

Crop	NFB Strain(s)	PSB Strain(s)	Key Synergistic Outcomes Reported	Reference
Wheat	*Paenibacillus beijingensis* BJ-18	*Paenibacillus* sp. B1	Increased biomass, plant N & P content, soil N & available P, soil nitrogenase activity (+69%), and plant *nifH* expression (doubled) vs. single inoculants	(11)
Chickpea	*Mesorhizobium ciceri*	*Pseudomonas* sp.	Increased nodulation, N & P uptake, grain yield	(18)
Chickpea	*Azotobacter chroococcum*	*Bacillus megaterium*	Increased N & P uptake, plant growth, yield	(19)
Chickpea	*Azotobacter brasilense*	*Bacillus* sp.	Increased seed yield and grain protein content	(16)
Maize	*Azospirillum brasilense*	*Pseudomonas fluorescens*	Increased shoot/root dry weight, N & P content	(20)

The development of effective co-inoculants or microbial consortia containing stress-tolerant NFB and PSB represents a promising strategy for enhancing wheat productivity and sustainability, particularly in environments subject to fluctuating water availability.

6. Challenges and Limitations in Using Stress-Tolerant Bioinoculants

6.1 Formulation and Shelf-Life Challenges

Using stress-tolerant nitrogen-fixing bacteria (NFB) and phosphate-solubilizing bacteria (PSB) in real farming conditions is not as straightforward as it seems in the lab. One of the main difficulties is finding the right carrier material that keeps the bacteria alive during production, storage, and field use. Carriers like peat, vermiculite, or liquid suspensions must protect the microbes from drying out, extreme temperatures, and sunlight while also being affordable and easy to use. However, since different bacteria have different needs, finding a one-size-fits-all solution is difficult. To be effective, the product must contain a sufficient number of living cells (more than 10^6–10^7 CFU per gram or milliliter) when applied to crops. Unfortunately, long storage times or poor handling often reduce their survival. While modern methods like encapsulation or immobilizing cells can improve stability, these are costly and complicated to produce on a large scale. This shows that more research is needed to improve how these beneficial microbes are preserved and delivered in farming.

6.2 Inconsistent Results in Field Conditions

Although bioinoculants perform well in laboratory trials, they often do not give the same results in real field conditions. Many factors affect how well they work. Soil type, pH, and organic content all influence whether the bacteria survive and function properly. These introduced microbes also have to compete with the natural soil bacteria, which can limit their effectiveness. In some cases, bioinoculants work better with specific wheat varieties, meaning their success can vary based on the crop and local environment. The method of applying these microbes—whether through seed coating, soil application, or foliar spray—also affects how well they work. All of these variables mean that bioinoculants need to be tested and adapted for each location to ensure they work consistently. Field trials across different conditions are important to make sure the products can deliver real benefits to farmers.

6.3 Regulatory and Practical Barriers

Bringing stress-tolerant bioinoculants into widespread use also involves regulatory, commercial, and practical challenges. One major issue is product quality—some commercial products do not contain the amount or type of microbes listed on their labels, which reduces farmers' trust. There is also a lack of clear and efficient regulatory systems for approving and monitoring these products, slowing their entry into the market. Farmers may not have enough information on how to store or apply bioinoculants properly, leading to poor results in the field. Moreover, since the results can vary, it is hard to show clear financial benefits, which makes farmers hesitant to invest in these technologies. Overcoming these issues will require cooperation between researchers, policymakers, and agricultural extension workers. Establishing clear standards, streamlining regulations, and providing practical training to farmers are all essential steps. Addressing these challenges is important to make sure bioinoculants can be a reliable part of sustainable wheat farming in tough growing conditions.

7. Future Perspectives and Research Directions

Looking ahead, the development of stress-tolerant bioinoculants should focus on identifying and improving bacterial strains that can survive and perform well under difficult conditions like drought, flooding, or poor soils. Exploring extreme environments—such as dry lands, saline soils, and flood-prone areas—may lead to the discovery of new strains with strong stress resistance. Future research should not only target bacteria that fix nitrogen or solubilize phosphate but also look for strains that can produce plant hormones, fight pathogens, and support overall plant health. Modern tools like genomics and proteomics can help scientists better understand how these bacteria function, making it easier to select or engineer strains with multiple useful traits.

Moving from single-strain products to well-balanced combinations of bacteria could also improve how bioinoculants work in real farm settings. For this, researchers need to study how different microbes interact with each other and with native soil organisms. These interactions are important for building stable and efficient microbial communities that can support crops under stress. Matching the right mix of microbes to specific soils and crops will be key to success. There is also a need to improve how bioinoculants are made and used. Better formulations that keep the bacteria alive during storage and help them reach plant roots effectively will improve results. New methods, such as microencapsulation and slow-release carriers, are promising but must be affordable and practical for farmers. Using these products with precision farming tools could further improve how they are applied in the field.

Field trials are essential to understand how these bioinoculants perform under real-world conditions. These trials should take place across different regions and growing conditions to provide reliable data. At the same time, more research is needed to understand how plants, microbes, and soil interact—especially under stress. This will help guide better application strategies. Finally, turning scientific knowledge into practical solutions requires strong policies, quality checks, and education programs. Farmers need clear information about how to use bioinoculants correctly and confidently. At the same time, governments and researchers must work together to ensure that these products are reliable, affordable, and backed by science. With the right support, stress-tolerant bioinoculants can play a big role in making agriculture more sustainable and resilient to climate change.

8. Conclusion

The use of stress-tolerant nitrogen-fixing (NFB) and phosphate-solubilizing bacteria (PSB) as bioinoculants offers a sustainable strategy to improve wheat growth in drought- and waterlogging-prone environments. These microbes support plant health by improving nitrogen and phosphorus availability, two key nutrients often limited under stress. Their survival under harsh conditions is aided by mechanisms like osmolyte production, biofilm formation, and ACC deaminase activity. Co-inoculation of NFB and PSB shows even greater promise, as their combined effects can improve nutrient uptake and stress tolerance beyond what single strains achieve.

However, practical challenges—such as ensuring product stability, consistent field performance, and regulatory approval—remain significant. Field conditions vary widely, and microbial interactions with native soils and crops can affect outcomes. Future research should focus on selecting robust, multi-functional strains, improving formulations for longer shelf life, and testing these products in diverse field settings. Integrating modern -omics tools with traditional microbiology can deepen our understanding of how bioinoculants work with plants and soils. With continued innovation and support, stress-tolerant bioinoculants could play a key role in making wheat production more resilient in the face of climate-related stress.

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