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Exploring Probiotic Postbiotics for Plant Growth Enhancement

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Abstract: *Probiotics are the group of microorganisms benefiting the plants by enhancing nutrient uptake, improving growth and boosting resistance to stress and disease. They offer a sustainable for chemical fertilizers and pesticides which promoting healthier plant growth improving overall crop yield. A major obstacle to agricultural sustainability is the growing worldwide demand for food combined with extensive soil deterioration. Conventional reliance on chemical fertilizers and pesticides has led to declining soil fertility, reduced microbial diversity, and increased vulnerability of crops to biotic and abiotic stressors. Microbial based treatment offers promising alternatives to sustainable agriculture practices, which are desperately needed to solve these problems. Probiotics, prebiotics, synbiotics and postbiotics have emerged as innovative methods to improve soil microbiota, encourage plant health, and reduce reliance on artificial inputs. Plant beneficial microorganisms 9PBM) not only boost nutrient mobilization and crop yield but also help to biodiversity conservation and resilience against climatic stress. Recent studies demonstrate the usefulness of postbiotics-supplemented nutrient solutions in hydroponic curly lettuce culture, where ATAGREEN formulation accelerated growth, boosted leaf and root development, and enhanced resistance to damaging organisms.*

Keywords: *Probiotics, Postbiotics, Plant Growth Enhancement.*

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1. Introduction

The global population is projected to exceed 9 billion by the year 2050, which will exert unprecedented pressure on food production systems. The need for sustainable intensification in agriculture has increased due to the quickening pace of urbanization, changes in dietary preferences, and an increase in the demand for high-value crops and animal products. Traditional farming practices, characterized by a heavy reliance on chemical fertilizers and pesticides, have reached their ecological limits.

Additionally, climate change exacerbates these issues by increasing the frequency of droughts, floods, and soil erosion, thereby jeopardizing global food security. The foundation of agricultural productivity is soil health, but due to widespread chemical use, it has significantly deteriorated over the past few decades. Soil organic matter has decreased, microbial diversity has changed, and nutrient imbalances have accelerated as a result of ongoing monoculture practices, overuse of synthetic fertilizers, and pesticide residues. Currently, problems like contamination, acidification, and salinity are common, and the amount of arable land is being reduced by desertification and erosion. This decline in soil fertility not only reduces crop yields but also undermines ecosystem services such as carbon sequestration and biodiversity conservation.

Agriculture must be done in an environmentally friendly way. It should conserve resources while meeting global food needs. Sustainable agriculture supports ecological balance, resource efficiency, and resilience to climate issues. It uses natural inputs, renewable resources, and suitable technologies to improve soil health, increase crop yields, and lessen reliance on synthetic chemicals. Importantly, sustainable methods must also consider social and economic factors to ensure they are affordable and accessible to all farmers. While chemical fertilizers and pesticides have increased yields in the past, their long-term effects are now clear. Over-fertilization leads to nutrient loss and water pollution.

In animal production, postbiotics from Lactobacillus plantarum strains have improved broiler growth performance during heat stress. They also enhance intestinal structure, adjust gut microbiota, and increase the expression of growth-related genes. This positions them as a potential substitute for traditional antibiotic growth promoters. Similarly, xylo oligosaccharides (XoS) combined with Lactobacillus cultures have shown antibacterial effects against multidrug-resistant Staphylococcus aureus found in mastitis cases in dairy cattle. This contributes to sustainable livestock health management.

Beyond agriculture and animal care, postbiotics could help prevent food allergies, change the gut microbiome, and shape the development of functional foods. Patent analyses show a significant rise in innovations focused on keeping the intestines healthy, fighting germs, and improving food preservation. Additionally, new nanomaterials like AIEE-type Supra-CDs work with both probiotic and postbiotic systems. This reduces the need for synthetic preservatives and allows for real-time monitoring of food safety. Overall, these studies support the idea that probiotics and postbiotics act not just as growth boosters and immune system regulators, but also as essential parts of sustainable production, environmental health, and human well-being. Future research should aim to create combined strategies, government guidelines, and targeted uses to fully take advantage of their benefits in farming, animal care, and clinical nutrition.

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2. Probiotics, Prebiotics, Synbiotics, and Postbiotics in Agriculture

Probiotics are live microorganisms which will provide health benefits to the host source when it is given in sufficient amount (Hill *et al.,*2014; Neef and Sanz, 2013) As per agriculture, the probiotics are referred as plant beneficial microorganisms (PBM) include, Lactobacillus, Bacillus, and *Pseudomonas*. PBM mechanism of action include nutrient mobilization, nitrogen fixation and phosphorus solubilization, production of phytohormones such as auxins, and gibberellins, and suppression of pathogens (microbial antagonism or biological control). Probiotics will also help in enhancing soil structure and microbial diversity which lead to improving crop resilience in stressful conditions

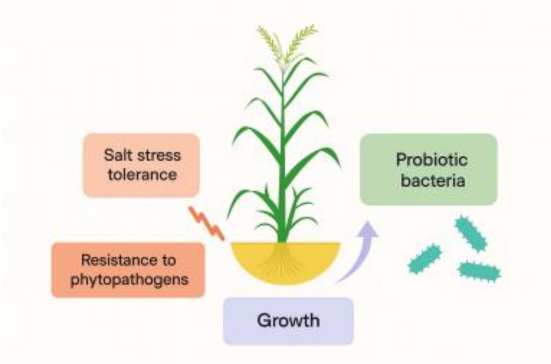

Figure 1: Overview of Probiotic Bcateria

Prebiotics, a non-digestible substrate that promote the growth of beneficial microorganisms that are naturally present in soil-plant system. It serves as carbon sources for indigenous microbes (improves soil conditions), they boost microbial diversity and the production of bioactive metabolites like short-chain fatty acids. In agriculture, it improves soil fertility and microbial equilibrium. Xylo oligosaccharides which derived from sugarcane bagasse have been shown to stimulate *Lactobacillus,* which indirectly inhibits multidrug-resistant *Staphylococcus aureus* in dairy environments.

Synbiotics, are the combination of probiotics and prebiotics which enhances microbial colonization and activity, leading to nutrient absorption, yield, provide bioactive compounds and stress resilience for crops.

3. Probiotic *Pseudomonas* communities enhance plant growth and nutrient assimilation

This study utilized 8 well-characterized plant growth promoting *Psedomonas* strains bacteria including *P. fluorescens* (1m1-96, F113, mvp1-4, Phl1c2, Q2-87), *P. protegens* (Pf-5, CHA0), and *P. brassicacearum* (Q8r1-96). These are allowed to cultured and preserve at −80 °C. A single colony of each bacterial strain was inoculated into LB broth (Luria-Bertani medium), grown overnight, washed with 0.85% NaCl, and standardized to OD at 600rpm gives 0.5 prior to use. They generated *Pseudomonas* consortia with variable diversity like 1,2,4 or 8 strains. There were 48 community combinations in total, following an equal representation approach assuring that strain variety and identify could be statistically separated.

The plant-microbe interaction experiment was conducted for 50 days using natural tomato field soil collected from Qilin, Nanjing, China. Surface sterilized the tomato seeds germinated on water agar and were first grown on γ-sterilized substrate. Seedling were moved into trays with

600 g of non-sterile soil per sub compartment (two plants each) once they reached the three-leaf stage. Ten days later, 5 mL of *Pseudomonas* inoculum at 5×10^2 cells g-1 soil was soaked into the plant roots. At 50 days, shoot biomass was harvested, oven-dried, and expressed as percent increase relative to the non-inoculated control.

The effects of probiotics *Pseudomonas* inoculant communities' diversity (number of strains) on their survival and development of advantageous characteristics in the tomato rhizosphere. The findings showed that a wider variety if inoculants produced superior root zone establishment and abundance, which boosted plant biomass and increased phosphorus, potassium, and iron nutrient intake. It's interesting to note that individual *Pseudomonas* strain identities had very little bearing, suggesting that diversity-driver ecological interactions were the main cause of the favorable results.

Pseudomonas abundance in the rhizosphere was closely linked with the reported gains in plant nutrients uptake, highlighting the significance of microbial survival for functional advantages. Low-richness communities may be untrustworthy because consistent strains may be lost during application, even if some of them had effects that were comparable to those of highly diverse communities.

Increasing microbial diversity within *Pseudomonas* inoculants seems to be a promising approach for improving rhizophore functioning and attaining more reliable and long-lasting plant growth promotion in agriculture.

4. Beneficial Plant-Associated Microorganisms

The reviewed beneficial latent microorganism may play a number of vital roles that support the health of plants and soil, including Plant growth promotion, biocontrol, and nutrient management. They have the special ability to improve soil fertility by reducing complicated nutrients to simpler forms. Nitrogen fixation, siderophore synthesis (iron-chelating chemicals), and phosphate solubilization are examples of specific functions. For soil and systemic health, they can create systemic resistance in hosts against a variety of disease and improve soil health by secreting extracellular metabolites. Both bacterial and fungal groups that serve as plant probiotics are described in the review.

Rhizobium are diastrophic, free-living bacteria develop a symbiotics connection with leguminous plants by creating root nodules that help fix nitrogen utilizing the nitrogenase enzyme. Additionally, they create siderophores, antibiotics, and improve phosphate solubilization, immunizing plants against infections through competition and antibiosis. *Azotobacter*, because of their quick proliferation and ability to preserve enzymes, these free-living, aerobic soil bacteria are widely known for fixing nitrogen. Additionally, they create Siderophores, which shield plants from phytopathogens by preventing them from accessing iron, and growth hormones (auxins, cytokines, and gibberellins).

Bacillus is a Gram-positive bacteria have large number in rhizosphere. To encourage plant development and defend against infections, they use both direct (nitrogen fixation, nutrient solubilization, hormone production) and indirect (antibiosis, systemic resistance) methods. Important phosphate solubilizers, such as *B.megaterium* and *B.subtilis*, can reduce drought and salt stress by producing exopolysaccharides (EPS). Cyanobacteria (Blue-Green Algae) is autotrophic prokaryotes are specifically used to boost the growth and yield of crops like rice. They actively participate in nitrogen fixation.

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5. Plant Growth Promoters (PGP) and Mechanisms

Beneficial bacteria and fungi that promote plant growth through both direct and indirect processes are included in the broad category of Plant Probiotics Microorganisms (PPM). Improving nutrient absorption and adjusting plant hormone balance are the main direct routes of action. These include biological nitrogen fixation, the phytohormones support root and shoot development, and the solubilization of vital minerals like phosphorus and iron through the formation of siderophores. PGPs also make direct roles; PGPs also make an indirect contribution by shielding plant from diseases and reducing stress.

In addition to producing a variety of antimicrobial chemical that inhibit phytopathogens, such as antibiotics, lytic enzymes, and volatile organic compounds, the activity of ACC deaminase helps plant maintain development by reducing ethylene levels under stress. A lot of PGPs boost plant defense mechanisms against biotic and abiotic stressors by activating induced systemic resistance (ISR).

5.1 Techniques for PPM Ecology Research

For PPM to be used biotechnology in crop management, it is crucial to comprehend its ecological function and interactions with plants. There are two primary methods used in the research of microbes linked with plants are

Culture-Dependent Approach: This conventional method entails separating microorganisms from the plant material, cultivating them, and then identifying them using a combination of molecular techniques (such as sequencing conserved DNA regions like the 16S rRNA gene for bacteria) and phenotypic techniques (morphological, physiological, and metabolic characteristics). Although helpful, these techniques are frequently tedious and time-consuming, and the outcomes can change according on the development conditions.

Culture-Independent Approach: Based on the extraction and analysis of DNA, this method enables the detection of microorganisms without the requirement for cultivation. This is important because many uncultivable microorganisms require unique ecological niches and symbiotic connections, which ordinary cultivation conditions frequently fail to replicate. Important methods consist of:

• Denaturing Gradient Gel Electrophoresis (DGGE): This technique rapidly profiles microbial populations by separating PCR products according to the DNA molecules' melting domain.
• Cloning and sequencing rRNA genes: These methods provide an accurate picture of species diversity and frequently uncover intricate bacterial communities.
• Next-Generation Sequencing (NGS): By providing deeper sequencing and the capacity to identify uncommon species that fully represent the microbial diversity within plant tissues, platforms like 454 pyrosequencing and Illumina have transformed detection.

6. Hydroponic Curly Lettuce Cultivation with ATAGREEN Postbiotic Solutions

Hydroponic systems serve as an effective platform for assessing microbial bio stimulants. A recent comparative investigation examined curly lettuce (Lactuca sativa var. crispa) cultivated under hydroponic conditions, both with and without the postbiotic addition of ATAGREEN.

Materials: Hydroponically cultivated lettuce plants in nutrient solutions.

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Treatments: Control: A standard nutrient solution devoid of postbiotics.

Lettuce plants were cultivated within a regulated hydroponic environment to assess the impact of ATAGREEN postbiotic supplementation. Two distinct growth conditions were examined: a control group receiving a standard nutrient solution, and an experimental group supplemented with an ATAGREEN postbiotic formulation. All growth parameters—including vegetative growth rate, leaf count, canopy structure, root development, and disease resistance—were systematically monitored throughout the growth cycle. As anticipated, the plants receiving the postbiotic treatment exhibited an increased leaf count, enhanced canopy structure, and more extensive and healthier root systems, facilitating superior nutrient absorption. Furthermore, the ATAGREEN treatment conferred enhanced resistance to pathogenic microorganisms, thereby indicating improved plant resilience and overall health in comparison to the control group.

6.1 Interpretation

This study illustrates that the incorporation of postbiotics significantly improves crop performance in hydroponic systems. By delivering active metabolites directly, ATAGREEN bolstered plant vigor while circumventing the use of live microbial cells, thereby mitigating ecological risks. This case emphasizes the potential of postbiotics as non-toxic, effective bio stimulants in contemporary agriculture.

6.2 Synthesis

The influence of probiotics and postbiotics on plant health extends beyond yield enhancement; it also includes the restoration of soil microbiomes, crop resilience, and the promotion of sustainable production systems. Probiotics enhance microbial diversity and directly impact plant roots, whereas postbiotics provide stable bioactive compounds that stimulate plant defense and growth. Together, they form a comprehensive strategy to lessen reliance on chemical inputs and rehabilitate degraded soils, thereby addressing global food demands sustainably.

6.3 Soil Fertility and Ecosystem Resilience

Soil fertility is fundamental to agricultural productivity; however, it has been significantly compromised due to years of intensive chemical fertilization and monocropping practices. The reduction in organic matter, along with salinization, acidification, and erosion, has diminished microbial diversity and disrupted the natural equilibrium of soil ecosystems. To restore soil fertility, it is essential to implement strategies that do not depend exclusively on chemicals but rather focus on biological approaches that enhance microbial diversity and create resilient soil.

One of the most important technologies for soil restoration is the use of microbial inoculants—preparations containing beneficial microbes, now accessible to farmers. These inoculants utilize bacteria, fungi, and consortia of plant-beneficial microorganisms (PBM) that are capable of nutrient cycling, improving soil structure, and aiding in pathogen suppression. Their functions encompass:

Nutrient mobilization includes processes such as phosphorus solubilization, nitrogen fixation, and the release of micronutrients; on the other hand, organic matter enhancement involves activities like the decomposition of plant residues and the stabilization of soil aggregates; additionally, biocontrol activities refer to the production of antimicrobial compounds that

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inhibit pathogens; furthermore, microbiome enrichment is a process through which microbial diversity lost due to chemical overuse is reintroduced into the soil.

The effects of climate change on agriculture are varied and encompass drought, salinity, temperature extremes, and nutrient imbalances. These challenges result in diminished plant growth rates, decreased yields, and accelerated soil degradation. To address these issues, the application of probiotics and postbiotics can be regarded as both viable and effective, as they promote plant health and enhance soil stability.

Abiotic stress tolerance can be enhanced through the synthesis of Osmo protectants and stress-related phytohormones, which bolster plant resilience against drought and salinity; Secondly, nutrient efficiency is improved by facilitating the uptake of nitrogen, phosphorus, and micronutrients in nutrient-deficient environments; Lastly, microbial equilibrium is restored by reestablishing soil microbial communities that have been disrupted by climate-induced stress.

Postbiotics serve as antioxidant activators, assisting plants in mitigating oxidation caused by extreme weather and drought, thereby prolonging their life cycle. Immune modulation refers to the ability of postbiotics to activate plant defense pathways, thus increasing their resistance to pathogens that thrive under stress conditions; Furthermore, by releasing organic acids and extracellular polysaccharides, postbiotics improve soil structure and water retention, consequently enhancing soil health.

Experiments conducted on hydroponic lettuce systems revealed that the application of ATAGREEN postbiotic nutrient solutions led to accelerated growth, enhanced root development, and increased resistance to harmful pathogens, thereby demonstrating the resilience of these systems in controlled cultivation environments. In livestock systems, the performance of broilers experiencing heat stress was notably improved through the use of postbiotics derived from Lactobacillus plantarum, highlighting their significance in alleviating production-related challenges faced by animals due to elevated temperatures. Regarding soil microbiome restoration, the combined use of probiotics and postbiotics proved effective in diversifying soil microbial populations that had been adversely affected by the excessive application of chemical fertilizers and stressors associated with climate change.

7. Applications in Crop Systems

Hydroponics is the nutrient solutions enriched with postbiotics promote the growth and resilience of leafy vegetables, including curly lettuce. Soil-based agriculture: Prebiotics help restore microbial diversity in degraded soils, while probiotics function as biofertilizers and biocontrol agents. Integrated systems approach reduces the reliance on chemical fertilizers and pesticides, thus minimizing soil degradation and environmental contamination.

8. Conclusion

In conclusion, probiotics and postbiotics represent a significant transformation in the future of agri-food systems. They possess the capability to reverse soil degradation, tackle challenges related to crop productivity, enhance livestock health, and ensure food safety, all while reducing reliance on chemical inputs. Research on ATAGREEN postbiotic supplementation in hydroponic lettuce, Lactobacillus plantarum postbiotics in broilers experiencing heat stress, and the application of lactic acid bacteria metabolites against Staphylococcus aureus in dairy systems exemplifies their adaptability and effectiveness.

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Once incorporated into food systems, probiotics and postbiotics serve as foundational elements of sustainability, aiding in the rejuvenation of soil fertility, increasing crop resilience to environmental stressors, boosting animal productivity, and offering natural bio preservation solutions. The forthcoming steps should focus on safety, standardization, regulatory frameworks, and precision application technologies. Furthermore, by integrating microbial-based products into organic and sustainable farming practices, agriculture can progress towards resilience, ecological balance, and global food security.

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