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Utilization of Biofertilizers and Plant Growth Promoters in Hydroponic Production System

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Over recent years, hydroponic agriculture has garnered increasing attention as an environmentally friendly and efficient method of cultivation. This review paper delves into the possibilities of enhancing hydroponics by exploring the use of biofertilizers and plant growth promoters (PGPs). Biofertilizers, which consist of beneficial bacteria and fungi, present an innovative approach to nutrient management, reducing the need for synthetic fertilizers. The paper investigates the application of Biofertilizers in hydroponic systems, assessing their potential to improve nutrient absorption, enhance plant health, and elevate crop yields in certain crops. Simultaneously, it scrutinizes the roles of PGPs, encompassing auxins, cytokinins, gibberellins, and other plant hormones, within the context of hydroponic crop development. Additionally, the review delves into the compatibility, recommended dosages and application methods of biofertilizers and PGPs in hydroponics, emphasizing their seamless integration with nutrient management strategies. The paper also addresses sustainable agricultural practices and their role in minimizing environmental

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impacts, thereby aligning biofertilizer and PGP application with the core principles of hydroponic cultivation. In conclusion, this comprehensive review offers valuable insights to hydroponic growers and researchers, enabling them to harness the potential of these natural partnerships for optimizing crop productivity while simultaneously reducing the ecological footprint of hydroponic systems.

Keywords: Biofertilizers; PGPs; synthetic fertilizers; hydroponic production.

1. INTRODUCTION

Hydroponics, an innovative soilless cultivation technique, has emerged as a compelling solution to the challenges posed by conventional agriculture. In this method, plants are grown in nutrient-rich water solutions rather than traditional soil, allowing for precise control over growing conditions and resource utilization [1]. The paramount importance of optimizing nutrient availability in hydroponic systems has spurred the exploration of novel strategies to enhance plant growth and productivity. Among these strategies, the utilization of biofertilizers and plant growth promoters has garnered significant attention due to their potential to revolutionize hydroponic crop production. Hydroponics offers a departure from conventional agriculture by providing a controlled environment that eliminates the uncertainties associated with soil-based cultivation [2]. In this system, nutrients are directly delivered to plants through nutrient solutions, ensuring efficient uptake and utilization. However, despite the precision that hydroponics affords, the challenge of maximizing nutrient absorption and utilization remains paramount to achieving optimal yields and crop quality. In this pursuit of nutrient optimization, biofertilizers and plant growth promoters present themselves as promising allies. Biofertilizers, comprising beneficial microorganisms, offer a natural means to improve nutrient availability, root health, and overall plant vitality. Meanwhile, plant growth promoters, encompassing hormones, enzymes, and microbial-based products, stimulate specific growth processes, accentuating the potential for elevated productivity [3]. In essence, the integration of biofertilizers and growth promoters in hydroponics emerges as a transformative avenue, holding promise for elevating yields, crop quality, and sustainability. As agricultural landscapes evolve, the exploration of these innovative strategies becomes not just a scientific endeavor, but a crucial step towards securing global food production in a resource constrained world [4]. In the face of mounting global challenges such as dwindling arable land, water scarcity, and the need for sustainable agricultural practices, hydroponic systems have emerged as a promising solution to revolutionize modern agriculture. Hydroponics, a soilless cultivation method, allows for precise control over environmental factors, nutrient delivery, and crop production. This innovative approach not only conserves water resources but also minimizes the use of synthetic fertilizers, which can have detrimental environmental consequences. In the pursuit of sustainable and eco-friendly farming practices, the integration of biofertilizers and plant growth promoters into hydroponic production systems has garnered significant attention. Biofertilizers, which encompass a range of beneficial microorganisms such as nitrogen-fixing bacteria and mycorrhizal fungi, offer the potential to enhance nutrient availability to plants while reducing the reliance on conventional fertilizers. Simultaneously, plant growth promoters, including natural hormones and microbial inoculants, have shown promise in stimulating crop growth, development, and stress tolerance. The rationale behind this research lies in the urgent need to explore and harness the synergistic potential of biofertilizers and plant growth promoters within hydroponics. By doing so, we aim to address several pressing agricultural and environmental challenges.

1. **Sustainability:** The depletion of arable land and the overuse of synthetic fertilizers have raised concerns about the sustainability of conventional agriculture. Hydroponic systems, when combined with biofertilizers and growth promoters, offer a more resource-efficient and sustainable alternative.
2. **Resource Efficiency:** Hydroponic cultivation already demonstrates impressive water savings compared to traditional soil-based methods. However, the incorporation of biofertilizers can further optimize nutrient utilization, reducing waste and runoff, and thus contributing to a more circular and efficient agricultural system.
3. **Environmental Impact:** Synthetic fertilizers are a significant source of water pollution and greenhouse gas emissions.

The reduction of their use through the implementation of biofertilizers aligns with global efforts to mitigate agriculture's environmental footprint.

4. **Crop Productivity:** Maximizing crop yields is crucial to meet the growing global food demand. Biofertilizers and growth promoters have the potential to boost crop productivity, ensuring food security in a changing world.

2. BIOFERTILIZERS AND PLANT GROWTH PROMOTERS

Within the realm of hydroponic agriculture, the incorporation of biofertilizers and plant growth promoters signifies a pivotal shift towards more efficient and sustainable crop cultivation methods. These interventions bring forth natural mechanisms that optimize plant growth, nutrient uptake, and overall system resilience.

2.1 Biofertilizers

Biofertilizers, representing a diverse array of beneficial microorganisms, have garnered substantial attention for their ability to amplify nutrient availability and foster robust root health. Nitrogen-fixing bacteria, for instance, establish a symbiotic relationship with plants by converting atmospheric nitrogen into a usable form, enhancing the nitrogen supply to plants. Similarly, phosphate solubilizing bacteria plays a crucial role in liberating bound phosphates in the growing medium, thereby augmenting phosphorus availability for improved plant growth. Microalgal biofertilizers fortify the nutrient reservoir and invigorate plant growth, while bacterial biofertilizers contribute to nutrient solubilization and root development through PGPR mechanisms [5]. Mycorrhizal biofertilizers hold promise for heightening nutrient uptake within hydroponic settings. These instances underscore the potential of biofertilizers to optimize nutrient dynamics and enhance the quality of crops in soilless cultivation setups like hydroponics.

Hydroponic agriculture stands as a beacon of innovation and sustainability in modern farming. It boasts precise control over environmental factors and nutrient delivery, offering an effective means to grow crops without soil. Within this innovative field, biofertilizers have emerged as a potent tool, harnessing the power of beneficial microorganisms to enhance nutrient availability and optimize plant growth in hydroponic systems [6,7].

3. HERE ARE SOME EXAMPLES OF BIOFERTILIZERS INTEGRATED WITH HYDROPONICS PRODUCTION SYSTEM

3.1 Tomato

Incorporating both biofertilizers and inorganic fertilizers into hydroponic systems can have a profound impact on various aspects, including the population of endophytic bacteria such as *Azotobacter* sp., *Azospirillum* sp., and PSB, as well as the overall nitrogen content of plants. However, it's worth noting that there wasn't a significant difference observed in the phosphorus (P) and potassium (K) content of the plants or their yield.

One notable outcome of this approach was the positive effect on tomato quality when 100% biofertilizer was used in combination with 50% inorganic fertilizer. This resulted in a remarkable 36% increase in fruit weight, with an impressive average fruit weight of 157.50 grams, firmly placing these tomatoes in the coveted grade A category. As a valuable consideration for future studies, the application of a 50% inorganic fertilizer within the fertigation system alongside biofertilizer proves to be a promising strategy. This approach not only addresses the issue of nutrient loss through evaporation but also contributes to enriching nutrient availability and subsequently enhancing tomato yields [8].

3.2 Basil

Multiple fresh leaf harvests can be carried out during a single growth cycle of basil. In the initial harvest, there was no significant difference in basil leaf yield when compared to the 50% control. However, in the second harvest, the application of mycorrhiza treatment led to a remarkable increase in basil yield, registering a substantial growth of 214.48% compared to the 50% control. Conversely, bacterial treatment resulted in a more modest increase of 17% in basil yield during this particular harvest.

In the third harvest, both bacterial and micro-algae treatments contributed to an enhanced basil yield. Specifically, bacteria led to an increase of approximately 19.20% when compared to the 50% control. When analyzing the cumulative harvest data, it becomes evident that bacteria, mycorrhiza, and micro-algae treatments collectively boosted basil yield by approximately 18.94%, 13.94%, and 5.72%, respectively, compared to the 50% control [9].

3.3 Baby Spinach

In hydroponic cultivation, the conditions in the root zone can be effectively managed. This study has revealed that by supplementing Arbuscular Mycorrhizal Fungi (AMF), Plant Growth-Promoting Rhizobacteria (PGPR), and microalgae to a nutrient solution reduced by 50% in a floating culture system, the detrimental effects of nutrient deficiency on spinach growth can be mitigated. While there was a decrease in both leaf yield and yield components, the supplementation led to notable enhancements in various quality parameters of spinach leaves. These improvements encompassed increased levels of total phenols, vitamin C, total soluble solids, chlorophyll, titratable acidity, as well as elevated concentrations of essential minerals such as iron, phosphorus, potassium, magnesium, manganese, and zinc. Notably, the nitrate content in baby spinach leaves exhibited a significant reduction.

In summary, our findings underscore the potential of biofertilizers as a means to substantially reduce the dependency on mineral fertilizers, potentially up to a 50% reduction. Furthermore, this approach has demonstrated the ability to elevate the quality of baby spinach, characterized by an augmentation of health-promoting compounds. Consequently, the integration of biofertilizers in the cultivation of soilless baby spinach emerges as a promising strategy for simultaneously advancing environmental sustainability and enhancing crop quality [10].

3.4 Plant Growth Promoters

In tandem with biofertilizers, plant growth promoters further bolster the potential of hydroponic systems by orchestrating key growth processes. These promoters encompass a spectrum of compounds, including hormones, enzymes, and microbial-based products, each serving to augment specific growth-related functions. Plant hormones, such as auxins, gibberellins and cytokinins act as regulators of growth and development, influencing cell division, elongation, and differentiation. Enzymes, on the other hand, facilitate nutrient absorption and metabolic activities critical for plant health. Collectively, plant growth promoters harmonize growth processes, accentuating nutrient uptake and utilization facilitated by biofertilizers. This synergy ultimately engenders plants that exhibit resilience against stressors, accelerated growth rates, and improved overall productivity.

In the dynamic and exacting world of hydroponics, where every element is meticulously controlled, the role of plant growth promoters (PGPs) emerges as a linchpin in achieving exceptional crop outcomes. These versatile agents, encompassing both natural hormones and beneficial microorganisms, serve as indispensable partners in orchestrating plant growth, enhancing stress resilience, and ultimately elevating yields within hydroponic systems [17]. PGPs function as nutrient mobilizers, ensuring that essential elements are readily absorbed by plants. This heightened nutrient efficiency is particularly invaluable in resource-conscious hydroponic systems.

Chart 1. Application of biofertilizers in hydroponics

Aspect	Application of Biofertilizers in Hydroponics
Introduction of Beneficial Microorganisms	Incorporate nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi into the hydroponic system [11].
Nitrogen Fixation	Enhance nitrogen availability by converting atmospheric nitrogen into plant-usable forms (ammonium or nitrate) [12].
Phosphorus Solubilization	Improve phosphorus accessibility by solubilizing insoluble phosphorus compounds in the nutrient solution [13].
Improved Nutrient Uptake	Facilitate better absorption of macronutrients and micronutrients, improving overall plant nutrition [14].
Enhanced Plant Growth	Promote root development and overall growth, leading to healthier and more productive hydroponic crops [15].
Sustainability	Support sustainable farming practices by reducing reliance on synthetic fertilizers and promoting eco-friendly nutrient management [16].

Beyond nutrient enhancement, PGPs are pivotal in modulating stress-responsive pathways. They empower hydroponic crops to withstand fluctuations in environmental conditions, such as temperature extremes, and provide a robust defense against pathogenic challenges. Perhaps the most compelling advantage of PGP utilization is its positive impact on crop yields. Growers frequently observe substantial increases in productivity, making PGPs a highly sought-after asset for hydroponic operations striving to maximize output and economic returns [18]. Incorporating PGPs into hydroponic systems signifies a holistic approach to growth optimization, addressing not just nutrient-rich growth but also resilience in the face of the dynamic and sometimes unpredictable conditions within hydroponics. As hydroponics continues to advance as a cornerstone of modern agriculture, the strategic deployment of PGPs remains pivotal in the pursuit of optimal crop performance and sustainable food production.

3.5 Range of Plant Growth Promoters

1.Auxins: At the forefront of plant growth regulation, auxins, with indole-3-acetic acid (IAA) as a primary representative, wield noteworthy influence over plant development. In hydroponics, auxins stimulate cell elongation, encouraging the growth of lateral roots, and exert control over apical dominance. These processes contribute to the creation of robust plant architecture, optimizing nutrient absorption and space utilization in the hydroponic environment [19].

2.Cytokinins: As masters of cell division and differentiation, cytokinins take center stage in hydroponics. Their presence prompts the development of lateral buds, resulting in expansive leaf growth and delayed senescence. This extended period of photosynthetic activity translates into a luxuriant foliage canopy and increased productivity [20].

3.Gibberellins: Gibberellins play a pivotal role in stem elongation, flowering initiation, and seed germination. In hydroponics, precise management of gibberellin levels allows growers to finetune the growth and development of crops, aligning them with specific growth phases and optimizing yield potential [21].

4.Microbial Inoculants: Integrating microbial allies, notably plant growth-promoting rhizobacteria (PGPR), adds a holistic dimension to hydroponic growth optimization. These beneficial microorganisms establish symbiotic relationships with plant roots, enhancing nutrient availability, fortifying root health, and strengthening defenses against pathogens. In hydroponics, PGPR proves invaluable for creating a resilient, nutrient-efficient, and harmonious growth environment [22,23].

3.5 Interplay of Diverse Plant Growth Promoters

1.Auxins, Cytokinins, and Gibberellins: These classical plant hormones often coexist within hydroponic environments, each playing its unique role in plant growth regulation. The synergy among auxins, cytokinins, and gibberellins fosters a balanced growth orchestra. Auxins stimulate root elongation, while cytokinins trigger cell division and leaf expansion. Gibberellins conduct stem elongation and flowering induction. When orchestrated harmoniously, these hormones ensure plants grow with optimal structure, foliage, and flowering, contributing to higher productivity [2,21] Tanimoto, [19].

2.Microbial Inoculants and Hormone Production: The introduction of microbial allies, particularly plant growth-promoting rhizobacteria (PGPR), adds another layer of complexity to the growth symphony. PGPR, in addition to their nutrient-enhancing abilities, often produce hormones like auxins and cytokinins themselves. This synergistic interaction between microbial-produced hormones and plant-endogenous hormones results in amplified growth signals, stimulating root development and nutrient absorption, thus enhancing overall plant vigor [22,24].

4. APPLICATION OF PLANT GROWTH PROMOTERS IN HYDROPONICS

4.1 Increase Nutrient Uptake

In hydroponic agriculture, the utilization of Plant Growth-Promoting Bacteria (PGPB) is a prominent research focus, with a particular emphasis on enhancing the uptake of key nutrients: nitrogen, phosphorus, and iron [25].

Nitrogen, essential for amino acids, chlorophyll, and nucleic acids, is typically sourced as ammonia or nitrate in plants. Nitrogen-fixing bacteria like *Rhizobia*, *Azospirillum*, *Azotobacter*, *Bacillus* and *Beijerinckia* play a pivotal role in converting atmospheric N_2 into ammonia. Hydroponic studies show that *Azospirillum* and Bacillus introductions into nitrogen-deficient environments result in improved nitrogen yield, shoot growth, and biomass in crops like bananas. Similarly, *Acinetobacter* and *Azotobacter* enhance nitrogen acquisition in duckweed and Choy sum. Combining nitrogen-fixing bacteria with mycorrhizal fungi doubles nitrogen uptake in lettuce. Additionally, nitrifying and ammonifying bacterial consortia exhibit promise in utilizing organic nitrogen in tomato crops, offering a potential shift towards organic fertilizers in hydroponics.

Phosphorus, vital for nucleic acids, photosynthesis, and root growth, is typically made more accessible to plants by phosphorus-solubilizing bacteria. These bacteria enhance phosphorus uptake in crops like lettuce and sorghum. Some beneficial organisms, such as *Pantoea agglomerans,* demonstrate both nitrogen fixation and phosphorus solubilization. Furthermore, microbial consortia improve photosynthesis and nutrient uptake in soybeans, suggesting potential benefits for both nitrogen and phosphorus.

Iron, a critical micronutrient crucial for chlorophyll production and enzymatic functions, is made more accessible by siderophore-secreting bacteria. Research highlights the role of these bacteria in enhancing iron uptake and crop biomass in canola and cucumber. In summary, the application of PGPB in hydroponics offers a promising avenue for optimizing nutrient uptake and crop growth, particularly concerning nitrogen, phosphorus, and iron, with potential implications for sustainable and organic nutrient management practices [25].

4.2 Regulate Hormones

ACC deaminase, used to regulate the plant hormone ethylene, is an effective approach for increasing hydroponic crop yields. PGPB carrying this gene were found even in the International Space Station. Among 20 bacterial species analyzed, *Pseudomonas agglomerans* and *Bacillus pyrocinnia* displayed multiple beneficial PGPB traits, including ACC deaminase, phosphate solubilization, and siderophore production. Canola yields increased by over 20% in studies using bacteria with ACC deaminase, IAA, phosphate solubilization, and siderophores. Strains with at least three functional plant growth-promoting traits, including ACC deaminase, consistently enhanced yields across various crops. Bacterial IAA, a growth-boosting auxin, was observed in successful PGPB like *Serratia marcescens* and *Pseudomonas putida* in cucumber crops. Consortium trials with IAA-producing bacteria significantly improved wheat yields. A group of auxin-producing bacteria also reduced banana seedling acclimatization time significantly, producing cytokinin, hydrocyanic acid, siderophores, and solubilizing phosphorus. *Gluconacetobacter diazotrophicus*, producing both IAA and gibberellin, increased lettuce yields. Bacteria with IAA, nitrogen fixation, and phosphorus solubilization enhanced rice yields. Pseudomonas fluorescens increased tomato crop yields, potentially through growth-regulating substances. Recent research found strains of *Pseudomonas fluorescens* with both IAA and ACC deaminase performed exceptionally well in various crops. PGPB with dual hormone production and enhanced nutrient uptake consistently excel in hydroponic and soil-based systems [25].

4.3 Symbiotic Enhancement

Both biofertilizers and plant growth promoters complement each other synergistically within hydroponic systems [26]. The biofertilizers establish an ideal environment around roots for the colonization of beneficial microorganisms, while growth promoters amplify the effects of these microorganisms by ensuring that the absorbed nutrients are efficiently utilized. In conclusion, the tandem application of biofertilizers and plant growth promoters represents a holistic approach to enhancing hydroponic crop production. By harnessing the capabilities of microorganisms and growth-regulating compounds, these interventions present a compelling avenue for maximizing nutrient efficiency, promoting robust growth, and fortifying the adaptability of plants within hydroponic environments. This synthesis of biological mechanisms holds promise in reshaping the future of agriculture towards more sustainable and productive outcomes.

5. BENEFITS OF INTEGRATING BIOFERTILIZERS AND GROWTH PROMOTERS IN HYDROPONICS

The incorporation of biofertilizers and growth promoters into hydroponic systems offers a multitude of advantages that positively influence plant growth, nutrient absorption, and overall crop production efficiency.

5.1 Why Biofertilizers Matter in Hydroponics?

1. **Unleashing Nutrient Accessibility:** Biofertilizers are adept at enhancing nutrient solubility, a transformation that renders essential elements such as nitrogen, phosphorus, and potassium readily available to plants. This phenomenon results in healthy plant growth and has the potential to boost crop yields significantly.
2. **Eco-Friendly Farming:** Beyond their nutrient-enhancing capabilities, the reduced dependency on synthetic fertilizers positions biofertilizers as ecological champions. They contribute significantly to mitigating the risk of nutrient runoff, soil contamination, and water pollution, thus aligning perfectly with sustainable farming practices and environmental conservation efforts.
3. **Enhanced Plant Resilience:** Mycorrhizal fungi, in particular, emerge as key players in bolstering a plant's resistance to various stress factors, including drought and diseases. This translates into healthier, more resilient crops, critical in the face of changing climatic conditions.
4. **Economical Advantage:** Beyond their ecological benefits, biofertilizers can potentially yield cost efficiencies over time. Growers can curtail their reliance on expensive synthetic fertilizers, thus reducing operational expenses [27].

5.2 Advantages of Leveraging PGPs in Hydroponics

1. **Enhanced Nutrient Utilization:** PGPs function as nutrient mobilizers, ensuring that essential elements are readily absorbed by plants. This heightened nutrient efficiency is particularly invaluable in resource-conscious hydroponic systems [28].
2. **Resilience to Stressors:** Beyond nutrient enhancement, PGPs are pivotal in modulating stress-responsive pathways. They empower hydroponic crops to withstand fluctuations in environmental conditions, such as temperature extremes, and provide a robust defense against pathogenic challenges [29].
3. **Amplified Crop Yields:** Perhaps the most compelling advantage of PGP utilization is its positive impact on crop yields. Growers frequently observe substantial increases in productivity, making PGPs a highly sought-after asset for hydroponic operations striving to maximize output and economic returns [18].

5.3 Enhanced Nutrient Uptake

Biofertilizers, particularly those containing beneficial microorganisms, establish symbiotic relationships with plant roots. These microorganisms colonize the rhizosphere, facilitating nutrient absorption. This leads to improved root development and function, resulting in a more efficient nutrient uptake process. As a consequence, plants experience accelerated growth, heightened health, and increased yields within the hydroponic environment [30].

5.4 Increased Disease Resistance

Selected microorganisms with antagonistic properties against plant pathogens are beneficial for the control of diseases and pests. These microorganisms can suppress the growth of detrimental pathogens and induce systemic resistance responses in plants. By fortifying the plant's natural defense mechanisms, biofertilizers contribute to reduced disease incidence, fostering healthier crops with fewer losses attributed to diseases [31].

5.6 Stress Tolerance and Adaptation

Plant growth promoters, encompassing hormones and enzymes, play a pivotal role in aiding plants to withstand environmental stressors. They regulate vital physiological processes such as water uptake, osmotic balance, and stress-related signaling pathways. This functionality proves particularly beneficial in hydroponics, where plants are exposed to fluctuations in nutrient levels, water availability, and other growth conditions [32].

5.7 Improved Nutrient Use Efficiency

A central benefit of employing biofertilizers and growth promoters in hydroponics is the potential for heightened nutrient use efficiency (NUE). These agents optimize nutrient uptake, minimizing nutrient wastage and reducing the requirement for excessive fertilization. This dual impact not only results in cost savings for growers but also contributes to a reduced environmental impact by curbing nutrient runoff [33].

5.8 Reduced Environmental Impact

Through the integration of biofertilizers and growth promoters, hydroponic systems can gradually reduce their dependence on conventional chemical fertilizers. This reduction in chemical inputs aligns with the principles of ecologically sustainable agriculture, decreasing the release of pollutants into the environment. As global concerns over environmental sustainability intensify, the adoption of practices that mitigate the carbon footprint and ecological consequences of agricultural practices becomes increasingly imperative [34].

5.9 Elevated Crop Quality

The utilization of biofertilizers and growth promoters has been linked to improvements in crop quality attributes. These enhancements encompass enriched flavor profiles, intensified coloration, and superior nutritional content. In hydroponic setups, characterized by controlled conditions conducive to precision agriculture, the introduction of these agents contributes to the cultivation of premium-quality crops. This aligns with consumer preferences for produce that offers superior taste and enhanced nutritional value. In conclusion, the integration of biofertilizers and growth promoters into hydroponic production methodologies confers a diverse array of benefits. These benefits encompass enhanced nutrient absorption, elevated disease resistance, stress resilience, heightened nutrient use efficiency, diminished environmental impact, and superior crop quality. These merits underscore the potential of these interventions to optimize hydroponic agriculture, advancing its sustainability and productivity [35].

6. INTEGRATION INTO HYDROPONIC SYSTEMS

The successful integration of biofertilizers and plant growth promoters into hydroponic systems requires a thoughtful approach that considers application methods, dosages, timing, and compatibility. Precise implementation of these interventions can harness their full potential and optimize plant growth within the controlled environment of hydroponics.

7. APPLICATION METHODS

Biofertilizers and growth promoters can be introduced into hydroponic systems through various application methods. One common approach involves incorporating them directly into the nutrient solution. This ensures that the microorganisms and growth-regulating substances are evenly distributed, providing plants with consistent access to these beneficial elements. Alternatively, they can be applied as foliar sprays, promoting direct contact with the leaves and facilitating rapid absorption [36].

7.1 Dosages and Timing

Determining the appropriate dosages and timing is essential for maximizing the benefits of these interventions. Underdosing might lead to suboptimal effects, while overdosing could potentially disrupt the delicate balance of the hydroponic system. Balancing these factors requires a thorough understanding of the specific requirements of the cultivated plants, as well as the characteristics of the biofertilizers and growth promoters being utilized.

8. COMPATIBILITY WITH HYDROPONIC SYSTEMS

The compatibility of biofertilizers and growth promoters with different hydroponic systems must be considered. Systems like nutrient film technique (NFT), deep water culture (DWC), and aeroponics each have distinct characteristics that influence nutrient availability, water distribution, and root exposure. Evaluating how biofertilizers and growth promoters interact with these systems is crucial to ensure that the interventions effectively reach the plants and exert their intended effects [37,38].

9. CONCLUSION

In the thriving realm of hydroponics, where precision and sustainability converge, our deep dive into the world of plant growth promoters (PGPs) has been nothing short of illuminating. As we draw the curtain on this comprehensive exploration, the significance of PGPs, encompassing natural hormones and symbiotic microorganisms, stands as a beacon of innovation and sustainability, breathing life into hydroponic ecosystems. Our hydroponic odyssey has unfurled a tapestry of diverse plant growth promoters – the auxins, cytokinins, gibberellins –

dancing in harmony with microbial allies. Together, they compose a symphony of growth, finely tuning nutrient utilization, bolstering resilience against environmental stressors, and orchestrating a crescendo of crop yields. This harmonious synergy ensures that hydroponic crops do more than merely survive; they thrive, bestowing upon us bountiful and exquisite harvests. The reverberations of PGP utilization extend far beyond the confines of hydroponic systems. They echo in the corridors of sustainability, where resource efficiency and ecological harmony hold sway. The judicious management of nutrients, bolstered resilience, and enhanced yields collectively herald a more sustainable and resource-conscious approach to agriculture. In an era where global food demands escalate alongside pressing environmental challenges, hydroponics, enriched by PGPs, emerges as a guiding star, illuminating a path towards the future of food production that marries ecological stewardship with economic viability. Our shared journey, one marked by growth and collaboration, underscores the vital role of PGPs in hydroponics. It is a testament to our capacity to harness the power of nature and scientific innovation in tandem, to nourish a burgeoning global population while safeguarding the finite resources of our planet. In conclusion, hydroponics is more than a method; it's an affirmation of human adaptability and ingenuity. With PGPs as steadfast allies, we embark on a trajectory that holds the promise of a more sustainable, efficient, and lush agriculture. As we bid adieu to this exploration, envision a future where hydroponic landscapes teem with abundance, enriching our lives and nurturing a world hungry for sustenance. This captivating journey concludes our exploration into the realm of biofertilizers and plant growth promoters within hydroponic production systems. May your hydroponic endeavors continue to flourish, yielding ever more opulent harvests, and may these fruits of innovation sustain us now and for generations to come.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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