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Synergistic effects of microbial inoculants and reduced nutrients on hydroponic lettuce performance and profitability

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ABSTRACT

This study, conducted in Maguindanao, Philippines, addresses the high costs and environmental impacts of chemical fertilizers in hydroponics by investigating the integration of microbial inoculants with reduced-rate nutrient solutions for loose-leaf lettuce cultivation. The research used a factorial design, assessing three nutrient levels (100% recommended rate, 50%, and tap water) and four microbial conditions: no inoculant, *Azospirillum brasilense*, Vesicular Arbuscular Mycorrhizae (VAM), and a combination of both. A strong synergistic interaction was discovered. The treatment combining a 50% nutrient solution with both *A. brasilense* and VAM yielded the highest marketable biomass (446.67 g/plant), significantly surpassing the standard 100% nutrient treatment (372.51 g). Conversely, adding inoculants to the full-strength nutrient solution often suppressed plant growth. Economic analysis confirmed that the synergistic 50% nutrient and combined inoculant strategy also generated the highest annual net income, making it the most commercially viable approach. These findings demonstrate that integrating multi-strain microbial inoculants with a half-strength nutrient solution is an economically advantageous and sustainable strategy to reduce fertilizer dependency, lower production costs, and enhance hydroponic lettuce cultivation.

Keywords: *Azospirillum brasilense,* VAM, Nutrient solution, *Lactuca sativa.*

Efeitos sinérgicos de inoculantes microbianos e nutrientes reduzidos no desempenho e rentabilidade da alface hidropônica

RESUMO

Este estudo, conduzido em Maguindanao, Filipinas, aborda os altos custos e os impactos ambientais dos fertilizantes químicos na hidroponia, investigando a integração de inoculantes microbianos com soluções nutritivas de dose reduzida para o cultivo de alface de folhas soltas. A pesquisa utilizou um delineamento fatorial, avaliando três níveis de nutrientes (100% da dose recomendada, 50% e água de torneira) e quatro condições microbianas: sem inoculante, *Azospirillum brasilense*, Micorrizas Arbusculares Vesiculares (MAV) e uma combinação de ambos. Foi descoberta uma forte interação sinérgica. O tratamento que combinou a solução nutritiva a 50% com ambos *A. brasilense* e MAV produziu a maior biomassa comercializável (446,67 g/planta), superando significativamente o tratamento padrão com 100% de nutrientes (372,51 g). Por outro lado, a adição de inoculantes à solução nutritiva de força total frequentemente suprimiu o crescimento das plantas. A análise econômica confirmou que a estratégia sinérgica de 50% de nutrientes e inoculantes combinados também gerou a maior receita líquida anual, tornando-a a abordagem mais viável comercialmente. Esses achados demonstram que a integração de inoculantes microbianos multiestirpe com uma solução nutritiva de meia força é uma estratégia economicamente vantajosa e sustentável para reduzir a dependência de fertilizantes, diminuir os custos de produção e melhorar o cultivo de alface hidropônica.

Palavras-chave: *Azospirillum brasilense*, MAV, Hidroponia, Solução nutritiva, *Lactuca sativa*.

1. Introduction

The global human population is projected to continue its rapid growth, placing unprecedented pressure on existing food production systems to meet escalating demands (Mourouzidou et al., 2022). Conventional agricultural practices, while historically successful in boosting yields, have often relied on intensive applications of synthetic chemical fertilizers and pesticides. This dependency has led to significant environmental consequences (Mourouzidou et al., 2022), including soil degradation, water contamination, loss of biodiversity, and contributions to greenhouse gas emissions (Gupta et al., 2015; Ekka, et al., 2023) Concurrently, there is growing consumer and regulatory demand for safer, more nutritious food produced through sustainable and ecologically sound methods. This confluence of pressures necessitates a change in thinking towards sustainable intensification, focusing on innovative strategies that enhance productivity while minimizing environmental impact and conserving natural resources (Mourouzidou et al., 2023; Kalamulla et al., 2022).

Controlled Environment Agriculture (CEA), particularly hydroponics, has emerged as a promising technology to address many of these challenges. Hydroponics, the practice of growing plants in a soilless medium using mineral nutrient solutions, offers numerous advantages over traditional field cultivation. These include substantially higher yields per unit area, up to 90% greater water use efficiency, year-round production capabilities, and reduced land requirements, making it ideal for urban and arid environments (Hooks et al., 2022).

Despite its efficiencies, conventional hydroponics is not without its limitations. The systems are heavily reliant on precisely formulated, chemically synthesized mineral nutrient solutions, which can be costly and energy-intensive to produce and transport (Folorunso et al., 2023). This reliance on synthetic inputs represents a significant operational expenditure and a potential bottleneck for economic sustainability, especially for small-scale growers (Filho et al., 2018). Furthermore, the exclusive use of inorganic nutrients can lead to produce with elevated nitrate concentrations and potentially lower levels of beneficial secondary metabolites (phytonutrients) compared to soil-grown crops, as the complex biological interactions of the soil rhizosphere are absent (Hooks et al., 2022). The potential for nutrient-rich effluent to contribute to environmental pollution through runoff also remains a concern if not managed in a closed-loop system (Folorunso et al., 2023; Dasgan and Temtek, 2022).

An increasingly researched strategy to enhance agricultural sustainability involves harnessing the power of beneficial soil microorganisms. Plant Growth-Promoting Microorganisms (PGPMs), a diverse group that includes Plant Growth-Promoting Rhizobacteria (PGPR) and Arbuscular Mycorrhizal Fungi (AMF), are recognized as key drivers of plant health and productivity (Jagadish and Chowdappa, 2021; Mustafa et al., 2019; Gupta et al., 2015). These microbes form intricate relationships with plant roots, enhancing growth through various mechanisms (Grover et al., 2021).

Direct mechanisms involve the direct facilitation of plant growth through the acquisition of nutrients and hormonal stimulation. This includes biological nitrogen fixation (BNF), where diazotrophic bacteria like Azospirillum convert atmospheric nitrogen (N2) into plant-usable ammonia and the production of phytohormones such as auxins, cytokinins, and gibberellins, which are crucial for modulating root architecture, stimulating cell division, and promoting overall plant development (Jagadish and Chowdappa, 2021; Grover et al., 2021; Cassán et al., 2020; Oliveira et al., 2023; Moreira et al., 2022).

While the benefits of PGPMs are extensively documented in conventional soil-based agriculture, their application and efficacy in soilless, static hydroponic systems remain a developing field of research (Aini et al., 2019; Dasgan and Temtek, 2022; Hooks et al., 2022; Moreira et al., 2022). The unique environment of a hydroponic solution - characterized by high concentrations of readily available ions, a liquid medium, and often limited microbial diversity - presents a fundamentally different ecological context than soil (Hooks et al., 2022; Moreira et al., 2022). This raises critical questions about the ability of soil-derived microbes to colonize plant roots, persist, and express their beneficial traits in such an environment.

Recent studies have demonstrated that plant growth-promoting rhizobacteria (PGPR) can enhance the growth, yield, and nutritional quality of hydroponically grown lettuce, suggesting the potential to transform these sterile systems into bio-integrated ecosystems (Aini et al., 2019; Dasgan and Temtek, 2022; Hooks et al., 2022). This study was designed to investigate this potential by systematically evaluating the interactive effects of commercially available microbial inoculants and varying concentrations of a standard hydroponic nutrient solution. Specifically, we aimed to assess the effects of two different PGPR/AMF inoculants (VAM and *A. brasilense* AbV5 and AbV6) on the growth and yield of loose-leaf lettuce. Additionally, we evaluated the impact of these inoculants in combination with a synthetic nutritional solution at both full and half rates. The study also included an economic analysis to evaluate the profitability of each integrated treatment, measured by Net Income and Return on Investment (ROI), to identify the most economically feasible production strategies that reduce reliance on synthetic inputs while maintaining or enhancing crop productivity.

The study hypothesized a strong synergistic effect where combining multi-strain microbial inoculants (*A. brasilense* + VAM) with a half-rate (50%) nutrient solution ½ RR SNAP) would create the most effective and profitable system, outperforming the conventional full-rate (100%) fertilizer, thereby achieving high yields while significantly reducing fertilizer costs. Conversely, the researchers hypothesized that adding these inoculants to the full-strength nutrient solution would be antagonistic, leading to suppressed plant growth due to high nutrient concentrations inhibiting microbial function. The core prediction was that this bio-integrated ½ RR approach would emerge as the optimal, most economically viable, and sustainable strategy for hydroponic lettuce production.

2. Material and Methods

The experiment was conducted over three consecutive cropping cycles in a controlled greenhouse at the Upi Agricultural College Research Station in Maguindanao, Philippines (7001'32"N, 124010'09E), with an elevation of 464 meters ASL and a type III climate, characterized by few pronounced seasons. It has a relatively dry season, from approximately November to April, and a rainy season for the rest of the year, with a short dry period of only one to three months.

The study followed a Randomized Complete Block Design (RCBD) with 12 treatments, each replicated three times. The treatments were structured as a 3x4 factorial arrangement, combining three nutrient solution levels (Tap Water, Half-Rate SNAP, and Recommended Rate SNAP) with four microbial inoculation conditions (no inoculant, *A. brasilense* (AbV5 and AbV6), VAM, and a combination of both). Each of the 36 experimental units consisted of a single hydroponic crate containing 20 loose-leaf lettuce plants (*L. sativa* L. cv. 'FanFare'), totaling 720 plants throughout the experiment.

A static, non-circulating Simple Nutrient Addition Program (SNAP) hydroponic system was utilized. This low-cost system utilizes 80 cm x 100 cm food-grade PE crates, each holding 40 liters of nutrient solution, with a perforated Styrofoam sheet serving as a plant float. The nutrient solutions were prepared using spring water. The Recommended Rate (RR) SNAP solution was created by sequentially adding 500 mL of SNAP A and 500 mL of SNAP B to 200 liters of water to prevent calcium precipitation. The half-rate (½ RR) SNAP solution was a 50% dilution of this full-strength solution.

Loose-leaf lettuce seeds were sown directly into 8-ounce Styrofoam pots filled with 100 grams of sterilized vermicast. The vermicast was sterilized in a pressure cooker at 15 psi for three hours on three consecutive days to eliminate native microorganisms. Ten days after sowing, seedlings were thinned to one healthy, uniform plant per pot.

Figure 1. The study setup consisted of 12 treatments, replicated three times.

For the designated treatments, 2 grams of the respective inoculant were thoroughly mixed into the 100 grams of sterilized vermicast in each pot before sowing.

The control treatments (T1, T2, T6) received only sterilized vermicast without any inoculant.

Three commercially available microbial inoculants were evaluated: 1) *A. brasilense* (AbV5 and AbV6) - A in-form biofertilizer containing the nitrogen-fixing rhizobacterium *A. brasilense* (AbV5 and AbV6) at 10^8 CFU/g. 2) VAM - A biofertilizer composed of spores and infective propagules of arbuscular mycorrhizal fungi (AMF). 3) *A. brasilense* (AbV5 and AbV6) + VAM: A multi-strain microbial consortium containing AMF as well as various beneficial bacteria, including nitrogen fixers, phosphorus solubilizers, and growth hormone secretors.

Growth parameters were measured at harvest, 45 days after sowing (DAS). Measurements included plant height (from collar to the highest leaf tip) and the total number of leaves. At harvest, the length of the longest root and total leaf area were also measured.

Yield parameters were recorded at harvest (45 DAS). Total fresh biomass was measured, and plants were sorted into marketable and non-marketable categories. The fresh weight of each category was recorded and converted to tons per hectare (t/ha^{-1}).

Postharvest quality was assessed daily on representative samples stored at room temperature. Visual quality was evaluated using a 1-9 hedonic scale, where a score of 5 represented the limit of marketability and a score of 3 represented the limit of edibility (Kader, 2002).

A cost and return analysis was performed to evaluate the economic viability of each treatment over one year for a projected 1,000-hill production system, using local prices for both fixed and variable costs. Average data from three trials were analyzed using analysis of variance (ANOVA), which is appropriate for a Randomized Complete Block Design (RCBD). When significant differences were found ($\alpha = 0.05$), Tukey's Honest Significant Difference (HSD) test was used for post hoc analysis to compare treatment means.

3. Results and Discussion

The integration of microbial inoculants with varied nutrient solution concentrations elicited significant and complex effects on the growth, yield, and economic viability of hydroponic lettuce, revealing a potent synergy that challenges conventional cultivation paradigms. The principal finding of this investigation is that a targeted combination of microbial inoculants with a half-rate nutrient solution not only compensated for the 50% reduction in synthetic fertilizer but produced yields numerically superior to the full-fertilizer standard. Specifically, the treatment combining a half-rate (½ RR) SNAP nutrient solution with a multi-strain consortium of *A. brasilense* and Vesicular Arbuscular Mycorrhizae (VAM), designated as T9, achieved the highest marketable yield at 446.67 g per five plants. This was statistically superior ($p = 0.024$) to the uninoculated tap water control (T1: 131.67 g) and notably 20% higher than the yield from the conventional full-rate (RR) SNAP fertilizer protocol (T2: 372.51 g).

A similar synergistic effect was observed for the treatment combining the half-rate solution with *A. brasilense* alone (T7), which yielded 432.42 g, also outperforming the full-fertilizer standard. These results strongly suggest that the relationship between nutrient concentration and microbial benefit is not additive but is defined by an optimal operational window of moderate nutrient stress. The peak performance of inoculants was observed exclusively at the 50% nutrient level, indicating that this condition creates an ideal ecological balance: it imposes sufficient nutrient limitation to incentivize beneficial microbial functions while providing the plant with an adequate mineral baseline to capitalize on these microbially-driven advantages.

The physiological basis for this pronounced synergy is multifaceted, involving direct microbial contributions to plant nutrition and the stimulation of more efficient plant morphology. The superior growth in the synergistic treatments was evident across key vegetative parameters. At harvest, plants in the ½ RR SNAP + *A. brasilense* + VAM treatment (T9) achieved the greatest height (21.01 cm), a stature statistically equivalent to plants grown in the full-fertilizer solution (T2: 20.98 cm) and significantly taller than the control (T1: 11.52 cm).

The robust vegetative development, likely stimulated by PGPM-produced phytohormones such as auxins, translated directly into a greater capacity for photosynthesis (Dasgan and Temtek, 2022; Aini et al., 2019; Prasad et al., 2019). This is supported by leaf area measurements, where the high-performing synergistic treatments, T7 (467.85 cm^2) and T9 (425.75 cm^2), developed canopies statistically comparable to the full-fertilizer treatment (T2: 503.60 cm^2) and significantly larger than the control (T1: 115.98 cm^2; $p = 0.003$) (Table 1). This enhanced growth is underpinned by the activation of key microbial functions under the nutrient-limited conditions of the half-strength solution.

The presence of *A. brasilense* facilitates biological nitrogen fixation (BNF), converting atmospheric nitrogen (N2) into a plant-usable form to supplement the reduced nitrogen supply (Dasgan and Temtek, 2022; Oliveira et al., 2023; Cassán et al., 2020; Moreira et al., 2022). Concurrently, PGPR within the consortium produce organic acids and enzymes, such as phosphatases, which solubilize and mobilize essential nutrients like phosphorus that may be bound to the vermicast substrate or precipitated in the solution (Jagadish and Chowdappa, 2021; Oliveira et al., 2023).

Perhaps the most compelling evidence of this enhanced efficiency is found in the plant's allocation of resources to its root system. Although not statistically significant ($p = 0.249$), the numerical trend in root length is highly informative. Plants in nutrient-poor conditions, such as the control (T1: 13.75 cm) and the inoculant-only treatment (T12: 14.63 cm), developed longer roots - a classic strategy to explore a larger volume for scarce nutrients.

Table 1. Three-cropping Cycle Effect of microbial inoculants and nutrient solution concentration on key growth and yield parameters of hydroponic lettuce at 45 days after sowing.

Parameters	Plant Height (cm)	Number of Leaves	Root Length (cm)	Leaf Area (cm²)	Total Fresh Biomass (g)	Marketable Yield (g)
T1: Control (Water)	11.52[a]	7.57	13.75	115.98[a]	220.05[a]	131.67[a]
T2: RR SNAP	20.98[b]	9.19	12.00	503.60[c]	566.58[cd]	372.51[bc]
T3: RR SNAP + *A. brasilense* (AbV5 and AbV6)	18.99[ab]	10.10	12.13	399.21[abc]	557.62[cd]	340.00[bc]
T4: RR SNAP + VAM	17.27[ab]	8.51	10.05	346.01[abc]	498.34[bcd]	310.17[ab]
T5: RR SNAP + *A. brasilense* (AbV5 and AbV6) +VAM	17.14[ab]	8.52	9.25	268.04[abc]	396.00[abcd]	219.52[ab]
T6: ½ RR SNAP	15.23[ab]	9.22	9.39	312.04[abc]	512.57[bcd]	326.64[abc]
T7: ½ RR SNAP + *A. brasilense* (AbV5 and AbV6)	20.34[b]	10.76	10.46	467.85[bc]	608.92[d]	432.42[c]
T8: ½ RR SNAP + VAM	13.73[ab]	8.11	10.35	254.56[abc]	386.32[abcd]	208.94[abc]
T9: ½ RR SNAP + *A. brasilense* (AbV5 and AbV6) +VAM	21.01[b]	10.28	8.93	425.75[bc]	564.67[cd]	446.67[c]
T10: H_2O + *A. brasilense* (AbV5 and AbV6)	13.65[ab]	9.07	7.37	284.56[abc]	361.66[abc]	278.33[abc]
T11: H_2O + VAM	13.71[ab]	9.05	13.05	291.36[abc]	364.40[abc]	273.33[abc]
T12: H_2O + *A. brasilense* (AbV5 and AbV6) +VAM	11.67[a]	8.60	14.63	191.88[ab]	296.66[abc]	201.66[ab]
p-value	**0.004**	**0.098**	**0.249**	**0.003**	**0.011**	**0.024**

Means in the same column followed by the same letter are not significantly different at p<0.05 according to Tukey's HSD test; cm – centimeters; g – grams.

In stark contrast, the highest-yielding synergistic treatment (T9) produced some of the shortest roots observed (8.93 cm). This is not an indication of poor growth but rather a hallmark of exceptional efficiency. The plant-microbe system was so effective at acquiring and delivering nutrients that a large, energetically expensive root system became unnecessary (Mustafa et al., 2019; Moreira et al., 2022; Ribeiro et al., 2022). The plant could, therefore, conserve carbon that would have been expended on root "foraging" and reallocate it to building photosynthetic machinery (leaves) (Grover et al., 2021) and marketable biomass. In this context, shorter root length functions as a powerful bio-indicator of the superior nutrient use efficiency of the integrated system.

To fully define the operational boundaries of this synergy, it is equally important to examine the consistent antagonism observed when inoculants were added to a full-strength nutrient solution. The addition of the multi-strain inoculant to the full-rate solution (T5) resulted in a marketable yield of only 219.52 g, a 41% reduction compared to the yield from the full-rate solution alone (T2: 372.51 g), and was economically unviable with a -28% ROI (Table 2). This refutes the assumption that combining beneficial inputs will yield additive results, which two primary mechanisms can explain. First, metabolic redundancy and feedback inhibition likely play a key role.

In a hydroponic solution saturated with readily available soluble nitrogen and phosphorus, microbial genes responsible for nutrient acquisition (e.g., the *nif* genes for nitrogen fixation) are typically downregulated, as there is no metabolic incentive for the microbes to perform these energetically costly functions (Prasad et al., 2019. Second, the high electrical conductivity (EC) of a full-strength hydroponic solution creates a saline environment that can induce osmotic stress in many soil-derived microbes, inhibiting their ability to colonize root surfaces and function effectively (Aini et al., 2019; Cassán et al., 2020; Hooks et al., 2022; Moreira et al., 2022; Oliveira et al., 2023). This finding establishes a crucial principle for bio-hydroponic systems: the chemical environment is an active, selective force, and one cannot simply "add" biology to an existing high-input chemical system without considering ecological implications.

The economic analysis translates these agronomic findings into compelling evidence of commercial viability, highlighting that the synergistic bio-integrated approach is not only scientifically sound but also the most profitable. The ½ RR SNAP + *A. brasilense* + VAM treatment (T9) generated the highest projected annual net income at USD 389.06, followed closely by the T7 treatment (½ RR SNAP + *A. brasilense*) at USD 373.84. These net incomes are more than double the profit generated by the conventional full-fertilizer protocol (T2: USD 163.31), presenting a powerful value proposition: a grower can simultaneously reduce fertilizer expenditures by 50% while more than doubling net profit.

Table 2. Economic analysis of hydroponic lettuce production based on a projected 1000-hill system over one year.

Parameters	Annual Production Cost (USD)	Annual Gross Income (USD)	Annual Net Income (USD)	Return on Investment (ROI, %)
T1: Control (Water)	159.19	174.58	15.4	10%
T2: RR SNAP	564.62	728.16	163.64	29%
T3: RR SNAP + *A. brasilense* (AbV5 and AbV6)	584.19	665.52	81.33	14%
T4: RR SNAP + VAM	593.98	606.80	12.82	2%
T5: RR SNAP + *A. brasilense* (AbV5 and AbV6) +VAM	593.98	428.67	(165.31)	-28%
T6: ½ RR SNAP	340.05	551.89	211.84	62%
T7: ½ RR SNAP + *A. brasilense* (AbV5 and AbV6)	356.98	731.33	374.36	105%
T8: ½ RR SNAP + VAM	356.44	352.12	(13.32)	-4%
T9: ½ RR SNAP + *A. brasilense* (AbV5 and AbV6) +VAM	365.44	755.03	389.59	107%
T10: H_2O + *A. brasilense* (AbV5 and AbV6)	159.19	370.49	211.31	133%
T11: H_2O + VAM	159.19	363.83	204.64	129%
T12: H_2O + *A. brasilense* (AbV5 and AbV6) +VAM	159.19	267.87	108.69	68%

Projections assume a farm-gate price of USD 1.72/kg. Production cycles per year vary based on the number of days required to harvest for each treatment.

It is also critical to distinguish between maximizing the rate of return (ROI) and maximizing absolute net income. While the inoculant-only treatments (T10 and T11) delivered the highest ROI percentages (133% and 129%, respectively) due to their extremely low input costs, their absolute net incomes were substantially lower than those of the synergistic treatments (Table 2). For a commercial enterprise, whose success depends on maximizing profit per unit of area and time, absolute net income is the more relevant performance metric. This analysis provides a data-driven business case for adopting sustainable technology, reframing it from a purely ideological choice to a rational economic decision.

A more detailed analysis of the differential performance among the inoculants offers crucial insights into which microbial traits are most valuable within the specific ecological context of a static hydroponic system. The consistent superior performance of the multi-strain *A. brasilense* + VAM consortium (T9) underscores the well-established advantage of functional redundancy, where a diverse consortium provides a broader spectrum of beneficial activities - including nitrogen fixation, phosphate solubilization, and phytohormone production - creating a more robust and resilient plant-microbe system. The strong performance of *A. brasilense* when applied alone (T7) highlights the pivotal role of nitrogen supplementation and hormonal stimulation, as its motility makes it particularly well-suited to colonize root surfaces within a liquid medium. The most striking result, however, was the comparatively poor performance of the VAM-only inoculant. In the ½ RR + VAM treatment (T8), the yield was lower than that of the uninoculated ½ RR solution (T6), and the treatment was economically unviable, with a negative ROI of -4%. This suggests that under these specific conditions, the VAM functioned as a net carbon drain on the plant.

As obligate biotrophs, Arbuscular Mycorrhizal Fungi (AMF) require an extensive physical substrate to form the hyphal networks necessary for their function (Kalamulla et al., 2022). The limited volume of vermicast within a static water culture was likely insufficient for their effective establishment. Consequently, the plant was likely allocating carbon to the fungus; however, the fungus, unable to establish a functional network, was not providing a proportional benefit in terms of nutrient uptake. This leads to a critical design principle: microbial selection must be precisely matched to the unique environmental conditions of the production system. Finally, postharvest evaluation demonstrated that this sustainable production method does not compromise product quality, as lettuce from the highest-yielding synergistic treatments (T7 and T9) remained edible for 5 to 7 days under ambient storage conditions (Table 3), a shelf life comparable to that of the full-fertilizer standard.

Taken together, these findings support a conceptual shift away from viewing hydroponics as a sterile, purely chemical-input system and toward a new paradigm of a "Bio-Integrated Hydroponic System." The simple addition of microbes or the complete elimination of fertilizers does not define this model. Rather, it is characterized by the intentional creation of an ecological balance, where a reduced, non-inhibitory level of mineral nutrients provides a foundation for a diverse and synergistic microbial community to thrive and actively enhance nutrient use efficiency. This approach directly addresses the primary economic and environmental challenges of conventional hydroponics.

Table 3. Postharvest visual quality score of lettuce crowns during 10 days of storage under ambient conditions.

Day of Storage	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
1	9	9	9	9	9	9	9	9	9	9	9	9
2	9	9	9	9	9	9	9	9	9	9	9	9
3	7	9	9	9	7	7	9	7	7	7	7	7
4	7	9	9	7	7	7	7	7	5	7	7	5
5	5	7	7	7	5	5	7	5	5	5	5	5
6	3	7	7	5	5	5	7	5	3	5	5	3
7	1	5	5	5	3	3	5	3	3	3	3	3
8	1	3	3	3	3	3	3	3	1	3	3	1
9	1	3	3	3	1	1	3	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1

Visual Quality Scale: 9=excellent, 7=good, 5=limit of marketability, 3=limit of edibility, 1=unusable.

For commercial producers, this study provides a clear, data-driven recommendation: the adoption of an integrated nutrient management strategy using a half-strength nutrient solution fortified with a high-quality, multi-strain microbial inoculant, as exemplified by the T9 treatment, represents the most promising pathway to reduce operating costs, substantially increase net income, and improve the overall sustainability of hydroponic lettuce production (Filho et al., 2018).

4. Conclusions

This study demonstrates that the most effective and profitable approach for hydroponic lettuce cultivation is a "Bio-Integrated Hydroponic System". This method combines a half-strength synthetic nutrient solution with a multi-strain microbial inoculant containing both *A. brasilense* and Vesicular Arbuscular Mycorrhizae (VAM).

This synergistic strategy significantly reduces the reliance on chemical fertilizers, cuts operational costs, and more than doubles the net income compared to conventional full-fertilizer hydroponics.

Therefore, the study recommends this integrated, hybrid model as the optimal path for commercial producers to enhance both the sustainability and profitability of their hydroponic operations.

Authors' Contribution

Marlon M. Garrigues conducted the practical fieldwork, data collection, and statistical analysis. Richel B. Garrigues was responsible for the initial conceptualization, experimental design, supervision, interpretation of the synergistic results, and economic analysis.

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