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Research Article

EFFECT OF *AZOSPIRILLUM*, *SINORHIZOBIUM*, AND *GLOMUS* ON THE GROWTH AND QUALITY OF *CARICA PAPAYA* L. IN GREENHOUSE

[a]Juan Ramiro Palomino-Malpartida, [b]Cayo García-Blásquez-Morote, [a]Roberta Esquivel-Quispe, [a]Jorge Luis Huamancusi-Morales, [a]José Antonio Quispe-Tenorio, [b]Susan Milagros Alarcón-Romaní, [b]Teresa Anghela Rojas-Cordero, [a,c]Francisco Espinoza-Montes

[a] *National University of San Cristóbal de Huamanga, Professional School of Agronomy, Peru.*
[b] *Plant Growth Promoting Bacteria Research Project (PGPR)-UNSCH-FOCAM, Peru.*
[c] *National University of Central Peru and Research Institute, UNSCH, Peru.*

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ABSTRACT

Papaya (*Carica papaya* L.) is a seed-propagated crop characterized by slow germination and high plant mortality. The use of plant growth-promoting microorganisms offers an alternative approach to achieving rapid, uniform germination and reduced mortality. The present study aimed to evaluate the effects of individual and combined inoculations of *Sinorhizobium meliloti*, *Azospirillum brasilense*, and *Glomus iranicum* on the agronomic characteristics and quality indicators of greenhouse-grown papaya plants. A 2 × 2 × 2 factorial experiment was conducted with the following treatments: *S. meliloti* (T1), *A. brasilense* (T2), *S. meliloti* + *A. brasilense* (T3), *G. iranicum* (T4), *S. meliloti* + *G. iranicum* (T5), *A. brasilense* + *G. iranicum* (T6), *S. meliloti* + *A. brasilense* + *G. iranicum* (T7), and a Control (T0). The results demonstrated that inoculation with the combined treatment of *S. meliloti* + *A. brasilense* + *G. iranicum* (T7), as well as *G. iranicum* alone (T4) and *S. meliloti* + *G. iranicum* (T5), resulted in significantly higher root weight, aerial part weight, total fresh and dry weight, enhanced growth, and a higher Dickson Quality Index. In conclusion, treatments T7 and T5 produced higher-quality plants in a shorter time, with reduced mortality, making them suitable for field transplantation. These findings provide a foundation for sustainable agriculture practices.

Corresponding Author: Francisco Espinoza-Montes
Email: francisco.espinoza@unsch.edu.pe

INTRODUCTION

Papaya (*Carica papaya* L.) is one of the most important tropical fruits worldwide, with the United States being the largest importer, accounting for an estimated 62% of global imports in 2023. This underscores the significance of papaya production and export (FAO, 2024). In Peru, papaya cultivation has grown rapidly in recent years, with exports in the form of fresh papaya, cooked or steamed papaya, and frozen pieces without added sugar or sweeteners, primarily destined for Chile, Spain, and Japan (AEDBLM, 2020).

Papaya propagation is typically done by seed, but the process is often slow, erratic, and incomplete (Chako and Singh, 1966), leading to high seedling mortality. This presents a significant challenge to production (Krishnanayak et al., 2024). Germination is a critical stage that requires an appropriate culture medium to supply essential nutrients for seedling survival (Mishra et al., 2017). To mitigate seedling mortality, the use of plant growth promoters, such as *Azospirillum* strain 245, has shown promise. This strain enhances root and vegetative development in young plants due to its ability to produce 3-indoleacetic acid (Bartolini et al., 2017; Licea-Herrera et al., 2020). Similarly, the application of mycorrhizal fungi can significantly and sustainably support the development and growth of vegetables and fruit trees (Thangavel et al., 2022).

Papaya, owing to its nutritional, medicinal, and industrial attributes, is in high demand under organic production systems (Alarcón et al., 2022). Organic production not only enhances post-harvest characteristics (Ruiz-Coutiño et al., 2019) but also involves the use of biofertilizers, which are inoculants containing live microorganisms capable of dissolving phosphates and silicates to promote plant growth (Naseer et al., 2020). Sangabriel-Conde et al. (2017) observed that intensive agronomic management of papaya reduces mycorrhizal colonization and the viability of arbuscular mycorrhizal fungi (AMF) species. These fungi form symbiotic relationships with 80% of terrestrial plants through their hyphae, contribute to the formation of the hyphosphere, participate in the nitrogen cycle, and reduce N_2O emissions from the soil (Li et al., 2023). Oliveira Filho et al. (2020) reported that AMF mitigates the effects of salt stress on papaya plants by protecting their nutritional, water, and biochemical components. Furthermore, López-Pérez et al. (2019) demonstrated a positive effect of AMF inoculation on the growth of papaya seedlings, indicating its potential for use in greenhouses and nurseries.

On the other hand, plant growth-promoting rhizobacteria (PGPR) inhabit the soil and are commonly found around plant roots. They reduce pathogen attacks and promote plant growth and development (Prasad et al., 2019). By producing various compounds, such as antibiotics, phytohormones, organic acids, and siderophores, PGPR solubilize nutrients, enhance their availability, and fix nitrogen, thereby contributing to plant health (Prasad et al., 2019). It is important to note that this phenomenon is complex and can be mediated by multiple mechanisms (Galindo et al., 2019; da Silva et al., 2023; Setiawati et al., 2023). These interactions are reflected in increased crop productivity (Arulbalachandran et al., 2020; Bonilla et al., 2021; Mishra et al., 2021). Moreover, PGPR contribute to soil health and fertility by mitigating the adverse effects of chemical fertilizers and reducing environmental pollution (Samri et al., 2021; Abdelsattar et al., 2023). In this context, Gureeva and Gureev (2023) observed that the application of *Azospirillum* exhibited a bioremediation effect on contaminated soils and induced resistance to both abiotic and biotic stress.

Each microorganism was selected for its ability to promote plant growth in various crops. To validate their effectiveness, they were tested on papaya plants. *Azospirillum brasilense* enhances the root system and facilitates nutrient transfer to plants, while *Glomus iranicum* var. *tenuihypharum* primarily solubilizes phosphorus, making it available to plants, and also contributes to biological control. Furthermore, *Sinorhizobium meliloti* fixes nitrogen and solubilizes nutrients for plant uptake, along with offering biological control benefits (Bashan and de-Bashan, 2010; Prasad et al., 2019; Cassán et al, 2014). In conclusion, the consortium of these microorganisms produces a synergistic effect that is greater than the effect of any single microorganism alone.

Recently, there has been growing scientific interest in the advantages offered by soil microorganisms and their potential as an effective alternative to reduce the use of chemical fertilizers. These microorganisms can help produce a greater number of plants in a shorter time, making them suitable for transplanting. Given their significance, the present study aimed to evaluate the individual effects and interactions of *S. meliloti*, *A. brasilense*, and *G. iranicum* var. *tenuihypharum* on the growth, development, vigor, and quality of papaya plants grown from seeds in a greenhouse setting.

MATERIALS AND METHODS

Location of the experiment

The greenhouse where the experiment was conducted was located on the campus of the National University of San Cristóbal de Huamanga, situated in the district of Ayacucho, province of Huamanga, Ayacucho region, at an altitude of 2,700 ms above sea level. The geographic coordinates are 13°8'43.20" south latitude and 74°13'19.95" west longitude.

Biological material

The experiment utilized inoculants based on the bacteria *S. meliloti* and *A. brasilense*, which were isolated, selected, and prepared in the laboratory. These inoculants were used in liquid formulations:

S. meliloti

S. meliloti was prepared at a concentration of 1×10^9 cfu/ml using a yeast-mannitol culture medium with Congo red indicator.

A. brasilense

A. brasilense was prepared at a concentration of 1×10^8 cfu/ml using NFb culture medium with bromothymol blue indicator.

Bacterial concentrations were determined using the viable plate count method, and inoculant purity was confirmed through Gram staining (García-Blásquez and Sato, 2019).

G. iranicum* var. *tenuihypharum

Moreover, the third inoculant used consisted of *G. iranicum* var. *tenuihypharum*, an AMF in the form of a commercial biological product, with a concentration of 120 propagules/ml of the substrate.

Selection and disinfection of seeds

The seeds were obtained from papaya fruits grown in the province of Huanta (2,300 m above sea level). After harvesting, the seeds were washed thoroughly to remove the aril and any adhering residues, and then air-dried at room temperature. Seeds were selected based on weight and subsequently disinfected by immersing them in a 5% sodium hypochlorite solution for 5 min. They were then rinsed five times with sterilized distilled water to ensure the removal of any residual disinfectant.

Germination and sowing

To induce germination, disinfected seeds were soaked for 24 h in a KNO_3 solution (2 g/L of water) as described by Barajas-Méndez et al. (2022). After soaking, the seeds were drained and dried using absorbent paper. They were then placed on trays lined with moistened paper to assess their viability at room temperature (25°C). After 7 days, 96% germination was observed, confirmed by the emergence of white radicles.

Viable seeds were sown in a 200-well plastic germination tray (3 × 3 cm per well), using 1.72 kg of substrate at field-capacity moisture. One seed was placed in each well at a depth of 1.5 cm.

Subsequently, vigorous and healthy seedlings were selected for transplantation. Each seedling was placed in a well of four 50-well growth trays (6 × 6 cm per well), using the same substrate at a rate of 4.15 kg per well, while maintaining optimal moisture levels. The seedlings were grown in a greenhouse under controlled conditions, including an average temperature of 25°C, 60% relative humidity, 16 h of light, 8 h of darkness, and controlled irrigation.

Plant inoculation by treatment

Fifteen days after the establishment of papaya plants in the test cells, inoculation with *S. meliloti* and *A. brasilense* was carried out by applying 2 ml per plant. The commercial inoculant based on *G. iranicum* was applied at a rate of 0.1 g per plant. Co-inoculations were also performed, combining: *S. meliloti* + *A. brasilense*, *A. brasilense* + *G. iranicum*, *S. meliloti* + *G. iranicum*, and *S. meliloti* + *A. brasilense* + *G. iranicum*. In the co-inoculations, the fungus was applied 10 days after the bacterial inoculation to avoid potential negative interactions. The microbial concentrations of the inoculants used are detailed in Table 1.

Table 1. The inoculant dose used in different treatments of papaya plants.

Treatments		*S. melilot*[1]	*A. brasilense*[2]	*G. iranicum*[3]
No.	Description	*(ml/plant)*	(ml/plant)	(g/plant)
T_0	Control	0	0	0.0
T_1	*S. meliloti*	2	0	0.0
T_2	*A. brasilense*	0	2	0.0
T_3	*S. meliloti* × *A. brasilense*	2	2	0.0
T_4	*G. iranicum*	0	0	0.1
T_5	*S. meliloti* × *G. iranicum*	2	0	0.1
T_6	*A. brasilense* × *G. iranicum*	0	2	0.1
T_7	*S. meliloti* × *A. brasilense* × *G. iranicum*	2	2	0.1

[1] The concentration of *S. meliloti* was 1×10^9 CFU/ml.

[2] The concentration of *A. brasilense* was 1×10^8 UFC/ml.

[3] The AMF inoculant *G. iranicum* var. *tenuihypharum* at 0.1g/plant.

Substratum

The substrate used was sterile peat, an inert, slightly acidic organic material with a high water retention capacity. It originates from plant remains such as bryophytes, lichens, and herbaceous plants from humid environments, forming under conditions that allow the conservation of plant material for thousands of years. These conditions include water saturation, low oxygen levels, and high acidity (CKPP, 2008).

Response variables

Agronomic characteristics

Treatments were applied at 30 days of age, and evaluations were carried out at 120 days of age.

Root length (RL)

It was measured with a millimeter ruler from the neck of the plant to the apical end of the main root.

Plant height (PH) and stem diameter (SD)

Plant height was measured with a millimeter ruler from the base of the stem collar to the apex. The stem diameter was determined three centimeters from the base of the plant, using a MITUTOYO vernier caliper with a precision of ± 0.0001 mm.

Fresh weight (FWA) and dry weight (DWA) of the aerial part

The samples were weighed using a precision balance (BOECO model BPS40PLUS) to obtain the fresh and dry weights. To obtain the dry weight, the samples were placed in paper bags and dried in an oven (MENMERT model UN55) at a temperature of 50°C until a constant weight was achieved.

Root fresh weight (RFW) and dry weight (RDW)

The same procedure was followed to determine these variables as for FWA and DWA.

Total fresh weight (TFW) and total dry weight (TDW) of the plant

These variables were determined by summing the aerial and root parts, as appropriate.

Plant quality indices

At the end of the experiment, the following indices were determined:

Morphological behavior (MB)

This was determined using the given below equation, proposed by Dalmasso et al. (1994).

MB = PH/RL

Where:

PH = plant height (cm)

RL = root length (cm)

Absolute growth rate (AGR)

This was determined using the equation presented by Di Benedetto and Tognetti (2016) as given below:

AGR = dW / dt

Where:

dW = Dry mass of green material

dt = Time unit

Slenderness coefficient (SC)

This was estimated using the equation proposed by Oliveira (1981) which is given below:

SC = PH / SD

Where:

PH = Plant height (cm)

SD = Stem diameter (mm)

Dickson quality index (DQI)

This was calculated using the given below equation which was developed by Dickson et al. (1960):

DQI = TSP / ((SC + DWA) / DWR)

Where:

TSP = Total dry weight of the plant (mg)

SC = Slenderness coefficient (mg)

DWA = Dry weight of the aerial part (mg)

DWR = Dry weight of the root (mg)

Statistical analysis

The study employed a 2 × 2 × 2 factorial experiment within a completely randomized design, with six replicates per treatment, to thoroughly evaluate the interactions among the factors under investigation. For the assignment of treatments to the experimental units (plants) in each tray, two treatments were randomly assigned, each with 25 seedlings. Therefore, four trays were used, resulting in a total of eight treatments. To compare the average effects and determine significant differences between treatments, the Tukey test was applied at a significance level of 0.05 ($p < 0.05$). Statistical analyses were performed using Infostat software (version 2008), as described by Di Rienzo et al. (2008).

RESULTS AND DISCUSSION

Agronomic characteristics

Root length, plant height, and stem diameter

Papaya plants inoculated with *S. meliloti* + *A. brasilense* (T3) exhibited greater root length ($p < 0.05$) compared to the control, with a difference of 4.0 cm. In contrast, shorter root length was observed in plants inoculated with *A. brasilense* + *G. iranicum* (T6), showing a difference of 1.34 cm compared to the control. Regarding plant height, those inoculated with *S. meliloti* + *A. brasilense* + *G. iranicum* (T7) had significantly greater heights ($p < 0.05$) compared to the control, with a difference of 2.92 cm. The lowest height was observed in plants inoculated with *A. brasilense* + *G. iranicum* (T6), which showed a difference of only 0.77 cm compared to the control. Regarding stem diameter, plants inoculated with *A. brasilense* (T2) had a larger diameter ($p < 0.05$) compared to the control, with a difference of 0.48 mm. The smallest diameter was observed in plants inoculated with *A. brasilense* + *G. iranicum* (T6), which was not significantly different from the control (Table 2).

Table 2. Morphological characteristics of papaya plants under greenhouse conditions.

Treatments		Root length (cm)	Plant height (cm)	Stem diameter (mm)
No.	Description			
T_0	Control	11.83 b	8.33 d	2.52 abc
T_1	*S. meliloti*	14.67 ab	10.92 ab	2.50 bc
T_2	*A. brasilense*	15.00 ab	9.30 cd	3.00 a
T_3	*S. meliloti* × *A. brasilense*	15.3 a	10.08 abc	2.65 ab
T_4	*G. iranicum*	13.92 ab	10.32 abc	2.67 ab
T_5	*S. meliloti* × *G. iranicum*	14.17 ab	9.83 bc	2.88 ab
T_6	*A. brasilense* × *G. iranicum*	13.17 ab	9.10 cd	2.10 c
T_7	*S. meliloti* × *A. brasilense* × *G. iranicum*	13.42 ab	11.25 a	2.97 ab
p-value		<0.001		

a,b,c Different letters in columns are significantly different from each other ($P < 0.05$).

Plants inoculated with *S. meliloti* + *A. brasilense* (T3) exhibit morphological and physiological changes in the root system, leading to increased root length and plant height. This improvement is attributed to the microorganisms creating favorable conditions for plant growth and development, including enhancing nutrient availability in the soil (Lima et al., 2011; de Matos et al., 2018; Samri et al., 2021), fixing nitrogen (Galindo et al., 2019; da Silva et al., 2023; Setiawati et al., 2023), improving soil structure (Sankar et al., 2017; Licea-Herrera et al., 2020), and increasing plant resistance to diseases (Prasad et al., 2019).

These results align with previous studies demonstrating the positive effects of microorganisms on plant growth. For example, Hidalgo et al. (2021) and López-Pérez et al. (2019) studied mycorrhizal fungi and found that they promote the vegetative growth and development of papaya. These findings were also confirmed by Barajas-Méndez et al. (2022). Furthermore, Dutta et al. (2010), under field conditions, and Bakhshish et al. (2022), under nursery conditions, showed that inoculation with *Azospirillum* and other microorganisms improves the growth and development of papaya plants.

Fresh weights

The fresh weights of roots, shoots, and total biomass of papaya plants inoculated with *S. meliloti* × *G. iranicum* (T5) were significantly higher than those of the other treatments. However, the treatments inoculated with *A. brasilense* (T2) and *S. meliloti* + *A. brasilense* + *G. iranicum* (T7) also showed statistically similar results to T5 in terms of root fresh weight and total plant weight (Table 3).

The interaction between microorganisms likely stimulated root growth, enhancing soil exploration and the uptake of nutrients and water, which in turn promoted the development of aboveground biomass. Moreover, the role of plant growth-promoting microorganisms in enhancing photosynthetic activity should not be overlooked, as it directly impacts plant development (Gaiotto et al., 2023). Furthermore, these microorganisms contribute to improved root colonization, leading to increased biomass production, chlorophyll content, and nutrient accumulation in seedlings (El Kinany et al., 2019).

These results align with previous studies that have demonstrated the significant effects of plant growth-promoting microorganisms on fresh weight. For instance, in *Capsicum annuum*, the use of rhizobacteria in plant nutrition yielded excellent results, significantly increasing the green weight of roots and shoots compared to non-inoculated plants under greenhouse conditions (Galeote-Cid et al., 2022). Similarly, Palomino et al. (2022) reported increased fresh weight of shoots and roots in avocado plants propagated via cuttings when treated with a combination of *A. brasilense* and indole-3-butyric acid under controlled conditions.

Table 3. Fresh weight of papaya plants grown under greenhouse conditions.

Treatments		Fresh root weight (mg)	Fresh weight of aerial part (mg)	Total fresh weight (mg)
No.	Description			
T_0	Control	600.17 b	835.33 d	1435.50 c
T_1	*S. meliloti*	609.00 b	884.00 cd	1493.00 c
T_2	*A. brasilense*	775.17 ab	1098.00 abc	1873.17 ab
T_3	*S. meliloti* × *A. brasilense*	638.00 b	957.83 bcd	1595.83 bc
T_4	*G. iranicum*	690.83 b	1022.00 abcd	1712.83 bc
T_5	*S. meliloti* × *G. iranicum*	921.17 a	1200.83 a	2122.00 a
T_6	*A. brasilense* × *G. iranicum*	622.00 b	860.67 d	1482.67 c
T_7	*S. meliloti* × *A. brasilense* × *G. iranicum*	774.83 ab	1181.50 ab	1956.33 ab
p-value		<0.001	<0.001	<0.001

[a,b,c] Different letters in columns are significantly different from each other ($P < 0.05$).

Dry weight

Regarding dry weights, plants inoculated with *S. meliloti* + *G. iranicum* (T5) were significantly superior compared to the other treatments. However, in the statistical comparison, the treatment inoculated with *S. meliloti* + *A. brasilense* + *G. iranicum* (T7) was similar to T5 in terms of aerial part dry weight and total plant dry weight. Additionally, the treatment inoculated with *A. brasilense* (T2) showed a similar total plant dry weight to T5 (Table 4).

The increased dry weight observed in plants inoculated with *S. meliloti* + *G. iranicum* (T5), along with the contributions of other plant growth-promoting microorganisms, suggests improved efficiency in converting fresh biomass to dry biomass. This improvement is likely attributable to enhanced nutrient absorption and reduced transpiration under controlled conditions. These findings underscore the critical roles of arbuscular mycorrhizal fungi and *Azospirillum*, which improve water retention capacity and alleviate water stress (Oliveira Filho et al., 2020). Furthermore, the interaction between *S. meliloti* and plant roots may have optimized biological nitrogen fixation, a key process for structural plant development (Moreira et al., 2020).

The ability of these microorganisms to improve dry weight supports the idea that microbial consortia can partially replace chemical fertilizers, as evidenced in previous studies (Nadeem et al., 2014). The results are consistent with earlier research demonstrating the positive impact of plant growth-promoting microorganisms on dry weight. For instance, Galeote-Cid et al. (2022) reported that the application of *Azospirillum* sp. significantly increased the dry weight of both roots and aerial parts in chili pepper plants under greenhouse conditions. Similarly, de Andrade et al. (2019) found that co-inoculation with *Azospirillum* sp. and *Burkholderia cepacia* yielded the highest aerial dry weight in strawberry plants (*Fragaria × ananassa*, Duch.), while *Azospirillum* sp. alone achieved the greatest root and total plant dry weights under greenhouse conditions. Moreover, Luciani et al. (2019) observed that the application of *G. iranicum* in the field enhanced photosynthetic activity in hazelnut (*Corylus avellana*), leading to more vigorous vegetative growth and higher plant dry weight.

These findings suggest that microorganisms promote root growth by producing phytohormones such as auxins, which expand the soil exploration area. They also facilitate nutrient solubilization, enhancing the availability of essential macronutrients and micronutrients. Moreover, a notable mechanism of action involves improving plant tolerance to biotic and abiotic stresses.

Quality indicators

Quality indicators provide valuable understandings about the adaptability of plants to environmental conditions. Metrics such as morphological behavior, absolute growth rate, slenderness coefficient, and the Dickson Quality Index (DQI) enable us to assess the potential success of plant establishment and development (Table 5).

Table 4. Dry weight of papaya plants observed under greenhouse conditions.

Treatments		Dry weight of root (mg)	Dry weight of aerial part (mg)	Total dry weight (mg)
No.	Description			
T_0	Control	69.00 d	98.33 d	167.33 c
T_1	*S. meliloti*	71.33 cd	105.50 d	176.83 c
T_2	*A. brasilense*	112.83 ab	183.50 ab	296.33 a
T_3	*S. meliloti* × *A. brasilense*	80.33 cd	139.50 bcd	219.83 bc
T_4	*G. iranicum*	101.83 abc	167.50 abc	269.33 ab
T_5	*S. meliloti* × *G. iranicum*	130.83 a	206.33 a	337.17 a
T_6	*A. brasilense* × *G. iranicum*	91.17 bcd	131.00 cd	222.17 bc
T_7	*S. meliloti* × *A. brasilense* × *G. iranicum*	117.83 ab	193.50 a	311.33 a
p-value		<0.001	<0.001	<0.001

[a,b,c] Different letters in columns are significantly different from each other (P ≤ 0,05),

Morphological behavior

Plants inoculated with *S. meliloti* + *A. brasilense* + *G. iranicum* (T7) exhibited the best morphological performance. This can be attributed to the role of *A. brasilense* in promoting the growth of both the root system and aerial parts (Bashan and de-Bashan, 2010). Moreover, the mycorrhizal symbiosis facilitated by *G. iranicum* enhances the absorption of essential nutrients, which are crucial for plant growth (Martin and van der Heijden, 2024). Improved morphological performance indicates a better physiological balance between the aerial and underground parts, which is critical for the long-term establishment and development of plants (Poorter and Sack, 2012).

Absolute growth rate

The results demonstrate that plants treated with *S. meliloti* + *G. iranicum* (T5), *S. meliloti* + *A. brasilense* + *G. iranicum* (T7), and *A. brasilense* (T2) achieved the highest absolute growth rates, significantly outperforming the other treatments (Table 5). This suggests greater efficiency in biomass accumulation, driven by the activity of PGPR and AMF (Zhang et al., 2023). Symbiotic bacteria like *S. meliloti* form nitrogen-fixing nodules that increase nitrogen availability in the form of NH_3, which, when assimilated by the plant, enhances its growth (Lipa and Janczarek, 2020). A higher absolute growth rate indicates a stronger growth potential during the early stages, which could translate into increased productivity in later phases. These findings align with previous studies demonstrating that microbial consortia improve growth rates in controlled environments (Egamberdieva et al., 2017).

Table 5. Quality indices of *Carica papaya* L. grown under greenhouse conditions.

Treatments		Morphological behavior	Absolute growth rate	Slenderness coefficient	Dickson Quality Index
No.	Description				
T_0	Control	0.72 ab	1.86 c	3.31 bc	35.40 cd
T_1	*S. meliloti*	0.76 ab	1.96 c	4.41 a	30.19 d
T_2	*A. brasilense*	0.64 b	3.29 a	3.13 c	63.03 ab
T_3	*S. meliloti* × *A. brasilense*	0.64 b	2.44 bc	3.85 ab	39.34 cd
T_4	*G. iranicum*	0.75 ab	2.99 ab	3.90 ab	49.15 bc
T_5	*S. meliloti* × *G. iranicum*	0.71 ab	3.75 a	3.41 bc	67.62 a
T_6	*A. brasilense* × *G. iranicum*	0.70 ab	2.47 bc	4.33 a	38.38 cd
T_7	*S. meliloti* × *A. brasilense* × *G. iranicum*	0.85 a	3.46 a	3.83 abc	57.91 ab
p-value		<0.01			

[a,b,c] Different letters in columns are significantly different from each other (P < 0.05).

Slenderness coefficient

The experiment revealed that plants inoculated with *S. meliloti* (T1) and *A. brasilense* + *G. iranicum* (T6) showed significantly higher slenderness coefficients compared to other treatments (Table 5). This indicates that the microorganisms in these treatments effectively support vertical growth without compromising plant sturdiness. This balance can be attributed to the ability of *A. brasilense* to stimulate stem elongation via phytohormone production and the structural support provided by *G. iranicum*, which enhances root architecture and nutrient absorption, ultimately supporting aerial growth (Gianinazzi et al., 2010). A high slenderness coefficient is advantageous for transplantation, as such plants are typically more stable and adaptable to new environments (Parra and Maciel, 2018).

Dickson quality index

In this study, plants treated with *S. meliloti* + *G. iranicum* (T5) were statistically superior to all other treatments, followed by *A. brasilense* (T2) and *S. meliloti* + *A. brasilense* + *G. iranicum* (T7) (Table 5). The DQI is an essential tool in intensive plant production, optimizing the selection of plants with high-quality traits. This, in turn, enhances the survival and growth of various plant species post-transplantation, increasing the likelihood of success in the field (Gallegos-Cedillo et al., 2021). As a reliable indicator of overall plant quality, higher DQI values represent greater resilience and adaptability to field conditions (Dickson et al., 1960).

CONCLUSIONS

The evaluation of microbial inoculation on papaya plant growth and development yielded the following observations:

1. Inoculation of papaya plants with the consortium of *Sinorhizobium meliloti*, *Azospirillum brasilense*, and *Glomus iranicum* (T7) promoted robust plant growth and development in a shorter time, making them suitable for transplantation to the field.
2. The co-inoculation of *S. meliloti* + *G. iranicum* (T5); *S. meliloti* + *A. brasilense* + *G. iranicum* (T7); and the inoculation of *A. brasilense* (T2) produced significantly higher and more consistent values for root, shoot, and total dry weights compared to other treatments.
3. The Dickson Quality Index was significantly higher in plants inoculated with *S. meliloti* + *G. iranicum* (T5), indicating greater robustness and improved structural quality.

RECOMMENDATION

Co-inoculation of *S. meliloti* + *G. iranicum* and *S. meliloti* + *A. brasilense* + *G. iranicum* is recommended for papaya cultivation in greenhouses. However, further research in nursery and field conditions is advised to optimize inoculant doses, explore other microbial interactions, and assess economic feasibility.

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AUTHORS’ CONTRIBUTIONS

JRPM, REQ, and JLHM conceived the idea and participated in the experimental design and supervision of the fieldwork; CGBM, SMAR, and TARC conducted the practical work; JAQT and FEM performed the data analysis, drafted the manuscript, and revised it; All authors reviewed and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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