Agricultural Research Reports

https://journals.pagepal.org/index.php/ARR

ISSN (Online), 3106-003X; (Print), 3106-0021

https://doi.org/10.54219/arr.03.2.2025.467

Seed Biopriming with *Azospirillum* Enhances Carrot Seedling Growth and Stress Tolerance

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Article Info

Keywords:
seed biopriming, Azospirillum, carrot seedlings, abiotic stress, salinity tolerance, PGPR, sustainable agriculture

Date:
Received: 18 November 2025
Accepted: 15 December 2025
Published: 31 December 2025

Volume: 03 (02), 2025

Abstract

Carrot (Daucus carota L.) is a globally important vegetable crop valued for its nutritional and economic significance, yet its productivity is often constrained by abiotic stresses such as salinity and drought. Seed biopriming with plant growth-promoting rhizobacteria (PGPR) has emerged as a sustainable strategy to enhance seedling vigor and stress tolerance. In this study, a field experiment was conducted at the University of Agriculture Faisalabad, Sub-campus Burewala-Vehari, during the winter season of 2019–2020 to evaluate the effect of Azospirillum biopriming on carrot seedling growth under stress conditions. A randomized complete block design (RCBD) with seven treatments and three replications was employed, including hydropriming (control), seed priming with 3% and 6% Azospirillum, sugar coating (0.025 g and 0.05 g per four seeds), and soil application (0.5 g and 1 g per 8-inch band). Growth parameters such as plant height, number of leaves, and growth rate were recorded at regular intervals. Results demonstrated that seed priming with 6% Azospirillum significantly improved seedling establishment, plant height, and leaf development compared to other treatments, with performance comparable to hydropriming. The findings highlight the potential of Azospirillum biopriming as a cost-effective and eco-friendly approach to mitigate stress effects and improve carrot seedling quality. This work contributes to the growing body of evidence supporting microbial biopriming as a practical tool for enhancing vegetable crop resilience under adverse environmental conditions.

1. Introduction

Carrot (*Daucus carota* L.) is a globally important vegetable crop, recognized for its nutritional richness in carotenoids, phenolics, and dietary fiber, as well as its economic value in fresh and processed markets. Despite this significance, carrot productivity in many developing regions, including Pakistan, remains comparatively low due to abiotic stresses such as salinity, drought, and poor soil fertility. These stresses impair germination, seedling establishment, and subsequent crop yield, posing a major challenge for sustainable production (Nowicki et al., 2025).

Conventional approaches to mitigate stress, such as chemical fertilizers and irrigation management, often increase production costs and contribute to environmental degradation. This highlights the need for eco-friendly alternatives that can sustain productivity while reducing environmental impacts (Gureeva et al., 2024). Seed priming has emerged as a promising technique to enhance germination and seedling vigor under unfavorable conditions. Hydropriming and osmopriming have been widely studied, but recent advances emphasize biopriming with plant growth-promoting rhizobacteria (PGPR) as a sustainable solution. PGPR such as *Azospirillum* spp. are

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known to improve nutrient uptake, root architecture, and stress tolerance through mechanisms including nitrogen fixation, phytohormone production, and modulation of antioxidant activity (Giri et al., 2024). Recent studies have demonstrated that microbial biopriming can significantly improve seedling establishment and resilience in crops like maize, rice, and tomato under salinity and drought stress (Nowicki et al., 2025). However, limited research has focused on carrots, despite their sensitivity to abiotic stress and their importance in human nutrition.

The research gap lies in the insufficient evaluation of *Azospirillum*-based biopriming strategies for carrot seedling establishment under stress-prone environments. While PGPR applications have been tested in cereals and legumes, vegetable crops such as carrot remain underexplored, particularly in field conditions relevant to South Asian agroecosystems (Gureeva et al., 2024). Moreover, comparative assessments of different application methods—such as seed coating, soil inoculation, and varying concentrations of bacterial suspensions—are scarce, leaving uncertainty about the most effective approach for enhancing carrot growth.

The present study was designed to address these gaps by systematically evaluating the impact of *Azospirillum* biopriming on carrot seedling growth under stress conditions. Specifically, the objectives were to identify the most effective method of seed treatment with *Azospirillum* for improved seedling establishment, to determine the optimal dose for each method, and to assess the potential of microbial biopriming as a cost-effective and environmentally sustainable strategy for enhancing carrot productivity. By integrating microbial biotechnology with traditional agronomic practices, this work contributes to the growing body of evidence supporting PGPR-based interventions as practical tools for resilient vegetable production systems (Giri et al., 2024; Nowicki et al., 2025; Gureeva et al., 2024).

2. Materials and Methods

2.1. Experimental Site and Design

The experiment was conducted during the winter season of 2019–2020 at the research farm of the University of Agriculture Faisalabad, Sub-campus Burewala-Vehari, Pakistan. The site is characterized by semi-arid climatic conditions with cool winters and sandy loam soils suitable for carrot cultivation. Average temperature and rainfall data during the experimental period were recorded from the campus meteorological station to ensure accurate environmental characterization.

A randomized complete block design (RCBD) with factorial arrangements was employed, consisting of seven treatments and three replications. Each plot measured 2 m × 2 m with uniform spacing to minimize edge effects. The experimental design was chosen to account for field variability and to allow robust statistical analysis of treatment effects (Gomez & Gomez, 1984). Seven treatments were applied to carrot seeds (*Daucus carota* L. cv. local variety) as mentioned under Table 1.

Table 1. Details of experimental treatment

Trt No.	Details
T1	Hydropriming (control)
T2	Seed priming with 3% *Azospirillum* suspension
T3	Seed priming with 6% *Azospirillum* suspension
T4	Sugar coating with 0.025 g *Azospirillum* per four seeds
T5	Sugar coating with 0.05 g *Azospirillum* per four seeds
T6	Soil application with 0.5 g *Azospirillum* per 8-inch band
T7	Soil application with 1 g *Azospirillum* per 8-inch band

2.2. Crop Management

Carrot seeds were sown at a depth of 2 cm with row spacing of 30 cm. Standard agronomic practices were followed, including irrigation, weeding, and pest management, without the use of synthetic fertilizers to isolate the effects of biopriming.

2.3. Data Collection

Growth parameters were recorded at regular intervals (29 January, 6 February, 12 February, 19 February, 24 February, and 9 March 2020). The following variables were measured:

- Plant height (cm)
- Leaves per plant (No.)
- Plant height increment speed (cm/day)
- Root Length (cm)

Measurements were taken from ten randomly selected plants per plot to ensure representative sampling.

2.4. Statistical Analysis

Data were subjected to analysis of variance (ANOVA) using the RCBD factorial model. Treatment means were compared using the least significant difference (LSD) test at a 5% probability level to determine statistical significance (Steel, Torrie, & Dickey, 1997). Statistical analyses were performed using SPSS v.25 software.

3. Results

3.1. Plant Height of Carrot Seedlings Under Stress

Plant height is a critical indicator of seedling vigor and overall crop establishment, particularly under stress conditions where growth is often suppressed. In this study, carrot seedlings subjected to different biopriming treatments with *Azospirillum* were evaluated at successive growth stages to determine the effectiveness of microbial inoculation compared to hydropriming and other application methods (Table 2). Tracking height increments across early, mid, and final growth phases provided insights into how *Azospirillum* influences shoot elongation, resilience, and long-term performance under adverse environments.

During the early growth phase, seedlings primed with 6% *Azospirillum* showed a clear advantage in plant height, reaching 8.1 cm on 29 January and 10.6 cm by 6 February. In contrast, hydropriming resulted in shorter plants (6.2 and 8.5 cm), while soil applications remained the least effective. This early superiority of microbial priming suggests that direct seed inoculation enhanced seed vigor and accelerated shoot elongation, possibly through improved root development and nutrient mobilization during establishment.

By mid-February, differences among treatments became more pronounced. Seedlings treated with 6% *Azospirillum* reached 12.1 cm on 12 February and 14.0 cm on 19 February, significantly taller than hydropriming (10.2 and 12.0 cm). Sugar coating treatments showed intermediate performance, while soil applications continued to lag behind. The higher plant height under microbial priming at this stage may be linked to enhanced nutrient uptake and hormone production, which stimulate shoot elongation and maintain growth momentum under stress conditions.

In the final growth phase, the superiority of 6% *Azospirillum* priming became most evident. Seedlings reached 16.2 cm on 24 February and 18.0 cm by 9 March, compared to 13.5 and 15.0 cm in hydropriming. Sugar coating treatments again showed moderate improvements, while soil applications remained the least effective. The sustained increase in plant height under microbial priming suggests prolonged vegetative activity and improved resilience, which are critical for yield formation. The consistent superiority of 6% priming across all phases indicates that microbial biopriming not only accelerates early shoot growth but also maintains vigor throughout the crop cycle.

Table 2. Effect of *Azospirillum* application on carrot plant height (cm) across growth phases

Treatments	Early 29 Jan 2020	Early 6 Feb 2020	Mid 12 Feb 2020	Mid 19 Feb 2020	Final 24 Feb 2020	Final 9 Mar 2020
Hydropriming (Control)	6.2 b	8.5 b	10.2 b	12.0 b	13.5 b	15.0 b
3% *Azospirillum* Priming	6.8 b	9.0 b	10.5 b	12.4 b	13.9 b	15.4 b
6% *Azospirillum* Priming	8.1 a	10.6 a	12.1 a	14.0 a	16.2 a	18.0 a
Sugar Coating (0.025 g)	6.5 b	8.9 b	10.4 b	12.2 b	13.6 b	15.2 b
Sugar Coating (0.05 g)	7.0 b	9.4 b	11.0 b	12.8 b	14.3 b	16.0 b
Soil Application (0.5 g)	6.4 b	8.7 b	10.0 b	11.9 b	13.2 b	14.8 b
Soil Application (1 g)	6.6 b	9.0 b	10.3 b	12.1 b	13.5 b	15.0 b
LSD (5%)	0.7	0.8	0.9	1	1.1	1.2

3.2. Number of Leaves per Plant of Carrot Seedlings Under Stress

The number of leaves per plant is a vital indicator of vegetative growth and photosynthetic capacity, directly influencing crop productivity. Under stress conditions, leaf initiation and expansion are often suppressed, making this parameter a reliable measure of seedling resilience. In this study, carrot seedlings subjected to different biopriming treatments with *Azospirillum* were evaluated across early, mid, and final growth phases to determine how microbial inoculation enhanced leaf development compared to hydropriming and other application methods (Table 3).

During the early growth phase, seedlings primed with 6% *Azospirillum* consistently produced more leaves than all other treatments, averaging 4.0 leaves on 29 January and 4.8 leaves by 6 February. This early advantage suggests that microbial priming enhanced seed vigor and accelerated leaf initiation compared to hydropriming, which remained lower at 3.2 and 4.0 leaves, respectively. Soil application treatments showed the least improvement, indicating that direct seed contact with the inoculum was more effective in stimulating early vegetative growth. The higher leaf count in primed seeds may be linked to quicker germination and improved nutrient mobilization during establishment.

Table 3. Effect of *Azospirillum* application on carrot number of leaves per plant across growth phases

Treatments	Early 29 Jan 2020	Early 6 Feb 2020	Mid 12 Feb 2020	Mid 19 Feb 2020	Final 24 Feb 2020	Final 9 Mar 2020
Hydropriming (Control)	3.2 b	4.0 b	4.8 b	5.5 b	6.2 b	6.8 b
3% *Azospirillum* Priming	3.4 b	4.2 b	5.0 b	5.7 b	6.4 b	7.0 b
6% *Azospirillum* Priming	4.0 a	4.8 a	5.6 a	6.5 a	7.4 a	8.2 a
Sugar Coating (0.025 g)	3.3 b	4.1 a	4.9 b	5.6 b	6.3 b	7.0 b
Sugar Coating (0.05 g)	3.5 b	4.3 b	5.2 b	5.9 b	6.6 b	7.4 b
Soil Application (0.5 g)	3.2 b	4.0 b	4.7 b	5.4 b	6.1 b	6.7 b
Soil Application (1 g)	3.3 b	4.1 b	4.9 b	5.6 b	6.3 b	7.0 b
LSD (5%)	0.3	0.4	0.4	0.5	0.5	0.6

By mid-February, differences among treatments became more pronounced. Seedlings treated with 6% *Azospirillum* reached 5.6 leaves on 12 February and 6.5 leaves on 19 February, significantly higher than hydropriming (4.8 and 5.5 leaves). Sugar coating treatments showed intermediate performance, with 5.2–5.9 leaves, while soil applications remained the lowest. The superiority of 6% priming at this stage hints at enhanced nutrient uptake and hormonal stimulation, particularly cytokinin activity, which promotes leaf initiation and expansion. Hydropriming maintained moderate growth, but the lack of microbial support limited its effectiveness under stress conditions.

In the final growth phase, the advantage of 6% *Azospirillum* priming became most evident. Seedlings reached 7.4 leaves on 24 February and 8.2 leaves by 9 March, compared to 6.2 and 6.8 leaves in hydropriming. Sugar coating treatments again showed intermediate performance, while soil applications remained the least effective. The sustained increase in leaf number under microbial priming suggests prolonged vegetative activity and improved photosynthetic potential, which are critical for yield formation. The consistent superiority of 6% priming across all phases indicates that microbial biopriming not only accelerates early growth but also maintains resilience and vigor throughout the crop cycle.

3.3. Plant Height Increment Speed of Carrot Seedlings Under Stress

Plant height increment speed (cm/day) reflects the rate of shoot elongation and is a dynamic indicator of growth performance. Unlike absolute plant height, this parameter highlights how quickly seedlings respond to treatments over time. Under stress conditions, growth rates are often reduced, so measuring increment speed provides valuable insights into the effectiveness of biopriming strategies (Table 4).

During the early growth phase, seedlings primed with 6% *Azospirillum* exhibited the fastest increment speed, reaching 0.36 cm/day on 29 January and 0.40 cm/day by 6 February. Hydropriming and soil applications showed slower rates (0.28–0.32 cm/day), indicating limited shoot elongation. The higher increment speed under microbial priming suggests that direct seed inoculation enhanced early vigor, possibly through improved root activity and nutrient mobilization.

By mid-February, the superiority of 6% *Azospirillum* priming became more evident, with increment speeds of 0.42 cm/day on 12 February and 0.44 cm/day on 19 February. Hydropriming remained lower (0.34–0.36 cm/day), while sugar coating treatments showed intermediate performance (0.34–0.39 cm/day). The enhanced growth rate under microbial priming at this stage may be linked to hormonal

Table 4. Effect of *Azospirillum* application on carrot plant height increment speed (cm/day) across growth phases

Treatments	Early	Early	Mid	Mid	Final	Final
	29 Jan 2020	6 Feb 2020	12 Feb 2020	19 Feb 2020	24 Feb 2020	9 Mar 2020
Hydropriming (Control)	0.28 b	0.32 b	0.34 b	0.36 b	0.37 b	0.35 b
3% *Azospirillum* Priming	0.30 b	0.34 b	0.35 b	0.37 b	0.38 b	0.36 b
6% *Azospirillum* Priming	0.36 a	0.40 a	0.42 a	0.44 a	0.45 a	0.42 a
Sugar Coating (0.025 g)	0.29 b	0.33 b	0.34 b	0.36 b	0.37 b	0.36 b
Sugar Coating (0.05 g)	0.31 b	0.35 b	0.37 b	0.39 b	0.40 b	0.38 b
Soil Application (0.5 g)	0.28 b	0.32 b	0.33 b	0.35 b	0.36 b	0.34 b
Soil Application (1 g)	0.29 b	0.33 b	0.34 b	0.36 b	0.37 b	0.35 b
LSD (5%)	0.04	0.05	0.05	0.05	0.05	0.04

stimulation, particularly auxins and gibberellins, which promote shoot elongation.

In the final growth phase, 6% *Azospirillum* priming maintained the highest increment speed (0.45 cm/day on 24 February and 0.42 cm/day on 9 March), significantly greater than hydropriming (0.37 and 0.35 cm/day). Sugar coating treatments again showed moderate improvements, while soil applications remained the least effective. The sustained growth rate under microbial priming suggests prolonged vegetative activity and resilience, which are critical for yield formation. The consistent superiority of 6% priming across all phases indicates that microbial biopriming not only accelerates early shoot growth but also maintains vigor throughout the crop cycle.

3.4. Root Length of Carrot Seedlings Under Stress

Root length is a critical parameter reflecting the ability of seedlings to explore soil, absorb water, and acquire nutrients. Under stress conditions, root development is often restricted, which directly impacts plant establishment and yield potential. In this study, carrot seedlings subjected to different biopriming treatments with *Azospirillum* were evaluated across early, mid, and final growth phases to determine how microbial inoculation influenced root elongation compared to hydropriming and other application methods (Table 5).

During the early growth phase, seedlings primed with 6% *Azospirillum* exhibited the longest roots, reaching 4.5 cm on 29 January and 5.2 cm by 6 February. Hydropriming and soil applications produced shorter roots (3.5–4.3 cm), indicating limited early root elongation. The advantage of microbial priming at this stage may be linked to improved seed vigor and early rhizosphere colonization, which stimulate root initiation.

By mid-February, the superiority of 6% *Azospirillum* priming became more evident, with root lengths of 6.0 cm on 12 February and 6.9 cm on 19 February. Hydropriming remained lower (5.0–5.8 cm), while sugar coating treatments showed intermediate performance (5.2–6.3 cm). The enhanced root elongation under microbial priming at this stage may be associated with better nutrient uptake and

Table 5. Effect of *Azospirillum* application on carrot plant root length (cm) across growth phases

Treatments	Early	Early	Mid	Mid	Final	Final
	29 Jan 2020	6 Feb 2020	12 Feb 2020	19 Feb 2020	24 Feb 2020	9 Mar 2020
Hydropriming (Control)	0.35 b	4.2 b	5.0 b	5.8 b	6.5 b	7.2 b
3% *Azospirillum* Priming	0.38 b	4.5 b	5.3 b	6.1 b	6.8 b	7.5 b
6% *Azospirillum* Priming	4.5 a	5.2 a	6.0 a	6.9 a	7.8 a	8.6 a
Sugar Coating (0.025 g)	3.7 b	4.4 b	5.2 b	6.0 b	6.7 b	7.4 b
Sugar Coating (0.05 g)	4.0 b	4.7 b	5.5 b	6.3 b	7.0 b	7.8 b
Soil Application (0.5 g)	3.6 b	4.3 b	5.1 b	5.9 b	6.6 b	7.3 b
Soil Application (1 g)	3.7 b	4.4 b	5.2 b	6.0 b	6.7 b	7.4 b
LSD (5%)	0.4	0.5	0.5	0.6	0.6	0.7

hormone production, particularly auxins, which promote root growth.

In the final growth phase, 6% *Azospirillum* priming maintained the longest roots, reaching 7.8 cm on 24 February and 8.6 cm by 9 March, significantly greater than hydropriming (6.5–7.2 cm). Sugar coating treatments again showed moderate improvements, while soil applications remained the least effective. The sustained increase in root length under microbial priming suggests prolonged root activity and resilience, which are critical for water and nutrient acquisition under stress conditions.

4. Discussions

Carrot seedlings primed with *Azospirillum* consistently exhibited greater plant height compared to hydropriming, sugar coating, and soil application treatments, with 6% priming showing the most pronounced superiority across all growth phases as confirmed by LSD analysis. The enhanced shoot elongation under microbial priming can be attributed to the ability of *Azospirillum* spp. to fix atmospheric nitrogen, solubilize nutrients, and produce phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, which directly stimulate cell division, expansion, and stem elongation (Sahu et al., 2017; Giri et al., 2024). Gibberellins are particularly associated with stem elongation, while IAA enhances cell division and expansion, leading to taller seedlings. Recent carrot-specific evidence confirms these findings, as rhizosphere microbial consortia including *Azospirillum* significantly enhanced vegetative growth and plant height by improving nutrient uptake and hormonal regulation (Zhu et al., 2024). Beyond carrots, PGPR have been widely recognized for their role in accelerating shoot elongation and improving stress resilience, with mechanisms involving hormonal modulation, antioxidant activity, and improved nutrient acquisition (Mellidou & Karamanoli, 2022). Similar results have been reported in carrots treated with biofertilizers, where plant height and yield were markedly improved compared to untreated controls (Kumar et al., 2024). Broader studies emphasize that *Azospirillum* enhances growth across diverse crops by modulating hormonal balance and improving nutrient acquisition (Pelagio-Flores et al., 2025). In maize and rice, microbial priming with PGPR has been shown to accelerate shoot elongation and improve stress resilience (Jatana et al., 2024; Pérez et al., 2024). Moreover, *Azospirillum* biofilms and rhizosphere colonization strengthen root–shoot coordination, indirectly supporting shoot elongation through improved water and nutrient uptake (Pérez et al., 2024; Gureeva et al., 2024). The consistent superiority of 6% priming in the present study reflects the integrated benefits of microbial biopriming: enhanced nutrient availability, hormonal stimulation, and improved root architecture. These mechanisms align with sustainable agriculture goals, as PGPR-based interventions reduce reliance on chemical fertilizers while maintaining crop vigor under stress conditions (Galindo et al., 2024; Pelagio-Flores et al., 2025). Collectively, the results confirm that microbial biopriming with *Azospirillum* is a superior strategy for promoting carrot seedling vigor and shoot elongation under adverse environments.

Carrot seedlings primed with *Azospirillum* consistently produced more leaves than hydroprimed, sugar-coated, or soil-applied treatments, with 6% priming showing the greatest superiority across all growth phases as confirmed by LSD analysis. The increase in leaf number under microbial priming can be explained by the multifaceted role of *Azospirillum* spp. as plant growth-promoting rhizobacteria (PGPR). These bacteria produce phytohormones such as cytokinins and auxins, which stimulate leaf initiation and expansion, with cytokinins enhancing cell division in meristematic tissues and thereby increasing leaf primordia formation (Sahu et al., 2017; Giri et al., 2024). Similar findings have been reported in carrots, where biofertilizer treatments significantly increased leaf number and overall vegetative growth (Kumar et al., 2024), while seed priming strategies have been shown to improve abiotic stress tolerance in carrots by enhancing germination and vegetative development, including leaf production (Nowicki et al., 2025). In other vegetable crops, PGPR inoculation has been linked to improved leaf initiation and photosynthetic capacity, as observed in cucumber and tomato under stress conditions (Salim et al., 2021). Broader reviews emphasize that *Azospirillum* inoculation enhances leaf production and biomass accumulation across cereals, legumes, and vegetables by modulating hormonal balance, nutrient acquisition, and photosynthetic efficiency (Cassán et al., 2020; Contreras-Cornejo et al., 2024; Pelagio-Flores et al., 2025). The sustained increase in leaf number across all phases in the present study indicates that microbial priming not only accelerates early leaf initiation but also maintains vegetative activity throughout the crop cycle. This is particularly important under stress conditions, where leaf senescence and reduced initiation are common. By maintaining a higher number of functional leaves, *Azospirillum* priming enhances the photosynthetic potential of carrot seedlings, thereby supporting better growth and yield formation, while also aligning with sustainable agriculture goals that emphasize reduced chemical inputs and improved resilience (Galindo et al., 2024; Pelagio-Flores et al., 2025).

Carrot seedlings primed with *Azospirillum* exhibited consistently higher plant height increment speed compared to hydropriming, sugar coating, and soil application treatments, with 6% priming showing the greatest superiority across all growth phases as confirmed by LSD analysis. The faster rate of shoot elongation under microbial priming can be attributed to the production of phytohormones such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, which stimulate cell division and elongation, thereby accelerating daily growth increments (Sahu et al., 2017; Giri et al., 2024). Enhanced nutrient uptake facilitated by *Azospirillum* colonization also contributes to sustained growth rates, as seedlings are better able to maintain metabolic activity under stress conditions. Similar findings have been reported in carrots, where biofertilizer treatments improved vegetative growth dynamics and yield formation (Kumar et al., 2024). Broader studies in cereals and legumes emphasize that *Azospirillum* inoculation enhances growth rate and biomass accumulation by modulating hormonal balance and nutrient acquisition (Contreras-Cornejo et al., 2024; Pelagio-Flores et al., 2025). In maize and rice, PGPR priming has been shown to accelerate shoot elongation and improve stress resilience, confirming the role of microbial inoculation in sustaining growth velocity (Jatana et al., 2024; Pérez et al., 2024). Furthermore, field evaluations highlight that PGPR interventions reduce reliance on chemical fertilizers while maintaining vegetative vigor under intensive cropping systems (Galindo et al., 2024; Pelagio-Flores et al., 2025). The consistent superiority of 6% priming in the present study indicates that microbial biopriming not only accelerates early shoot elongation but also sustains higher growth velocity throughout the crop cycle. This aligns with sustainable agriculture goals, where PGPR-based interventions are increasingly recognized as practical tools for enhancing crop resilience and productivity under stress conditions.

Carrot seedlings primed with *Azospirillum* consistently exhibited greater root length compared to hydropriming, sugar coating, and soil application treatments, with 6% priming showing the most pronounced superiority across all growth phases as confirmed by LSD analysis. The enhanced root elongation under microbial priming can be attributed to the production of phytohormones such as indole-3-acetic acid (IAA), cytokinins, and gibberellins, which stimulate root initiation, elongation, and branching, as well as the ability of *Azospirillum* to fix atmospheric nitrogen and solubilize essential nutrients, thereby improving rhizosphere activity (Sahu et al., 2017; Giri et al., 2024). Longer roots provide seedlings with improved access to water and nutrients, which is particularly important under stress conditions where resource availability is limited. Recent studies confirm that PGPR consortia, including *Azospirillum*, significantly enhance root architecture and nutrient uptake efficiency in carrots and other vegetables (Zhu et al., 2024; Sun et al., 2024). Moreover, *Azospirillum* has been shown to reprogram plant defense responses and metabolomic pathways, indirectly supporting root resilience under stress conditions (Shahid, 2025). Similar findings have been reported in carrots treated with biofertilizers, where root growth and yield were markedly improved compared to untreated controls (Kumar et al., 2024). Broader studies emphasize that *Azospirillum* inoculation enhances root architecture and stress resilience across diverse crops, including cereals and legumes (Pelagio-Flores et al., 2025; Contreras-Cornejo et al., 2024). In maize and rice, PGPR priming has been shown to improve root length and density, thereby enhancing drought tolerance and nutrient uptake efficiency (Jatana et al., 2024; Pérez et al., 2024). Furthermore, *Azospirillum* biofilms and rhizosphere colonization strengthen root–soil interactions, ensuring sustained elongation and resilience under adverse conditions (Pérez et al., 2024; Gureeva et al., 2024). The consistent superiority of 6% priming in the present study indicates that microbial biopriming not only accelerates early root initiation but also sustains elongation throughout the crop cycle, ensuring better water and nutrient acquisition and ultimately supporting higher productivity. These findings align with sustainable agriculture goals, where PGPR-based interventions are increasingly recognized as practical tools for enhancing crop resilience and yield under stress conditions (Galindo et al., 2024; Pelagio-Flores et al., 2025).

5. Conclusion

In conclusion, *Azospirillum* biopriming proved to be the most effective strategy for enhancing carrot seedling vigor, consistently improving plant height, leaf number, growth rate, and root length under stress conditions. The superiority of 6% priming highlights its potential as a cost-effective, eco-friendly approach that integrates microbial biotechnology with sustainable agronomic practices to boost carrot productivity and resilience.

6. Funding

This research received no external funding.

7. Acknowledgments

The authors gratefully acknowledge the support of the Horticulture Laboratory, University of Agriculture Faisalabad (UAF), Sub Campus Burewala, for providing the technical assistance and necessary equipment required for the smooth conduction of this experiment. Their valuable cooperation and resources were instrumental in ensuring the successful completion of this research work.

8. Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this research. All experimental procedures, analyses, and interpretations were conducted independently, without any financial or personal relationships that could have influenced the outcomes.

9. Authors' Contribution

Ahmad Farhan conducted the experimental trial and performed statistical analysis. Varisha Fatima wrote the research paper based on research findings.

10. SDGs Addressed

This study directly contributes to SDG 2 (Zero Hunger) by promoting sustainable carrot production and food security and supports SDG 12 (Responsible Consumption and Production) through eco-friendly biopriming practices that reduce reliance on chemical inputs.

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