Plant Archives Vol. 26, Supplement 2, 2026 pp.3533-3539 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.449

RESOURCE-EFFICIENT NUTRIENT MANAGEMENT ENHANCES MORPHOPHYSIOLOGICAL PERFORMANCE OF ONION (*Allium cepa* L.)

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(Date of Receiving : 22-05-2026; Date of Revision : 15-07-2026; Date of Acceptance : 31-07-2026)

ABSTRACT

The excessive dependence on chemical fertilizers in onion production necessitates the development of sustainable nutrient management strategies that enhance crop performance while reducing fertilizer inputs. Therefore, the present study was conducted during the rabi seasons of 2024-25 and 2025-26 to evaluate the effects of integrated application of biostimulants and biofertilizers on the growth and physiological attributes of onion (*Allium cepa* L.). The experiment was laid out in a split-plot design with three replications. The main-plot treatments comprised six nutrient management practices involving recommended dose of fertilizers (RDF) alone or in combination with foliar application of Ascophyllum extract (4%), Moringa leaf extract (4%), potassium humate (0.2%), and their combined application, whereas the sub-plot treatments consisted of sulphur-solubilizing bacteria (SSB), phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), and their combined application applied at 4.5 kg ha^{-1} each. Pooled analysis over two years revealed that the application of 75% RDF + Ascophyllum extract (4%) + Moringa leaf extract (4%) + potassium humate (0.2%) significantly recorded the highest plant height (67.68 cm), number of leaves (8.17 plant^{-1}), leaf length (61.88 cm), and chlorophyll content (5.57 mg 100 g^{-1}), representing marked improvements over the control. Among the biofertilizer treatments, the combined application of SSB + PSB + KSB produced the maximum plant height (66.95 cm), number of leaves (7.94 plant^{-1}), leaf length (60.69 cm) and chlorophyll content (5.21 mg 100 g^{-1}). The superior performance was attributed to enhanced nutrient solubilization and uptake, improved photosynthetic efficiency, and synergistic interactions between biostimulants and beneficial microorganisms. The results demonstrate that integrating 75% RDF with foliar application of Ascophyllum extract, Moringa leaf extract, potassium humate, and soil application of SSB, PSB, and KSB at 4.5 kg ha^{-1} each effectively improves vegetative growth and chlorophyll accumulation while reducing mineral fertilizer use by 25%. This integrated nutrient management approach offers a sustainable, environmentally sound, and economically viable strategy for improving onion production.
***Keywords* :** Ascophyllum extract, biofertilizers, biostimulants, integrated nutrient management.

Introduction

Onion (*Allium cepa* L.), belonging to the family Amaryllidaceae, is one of the most cultivated and economically important vegetable crops in the world. It is highly appreciated due to its culinary diversity, long shelf-life and substantial nutritional benefits (Cordeiro *et al.*, 2022). With a production of 288.77 lakh tonnes during 2024-25, India is the second largest producer of onions in the world, which is a substantial contributor to national food security and farmers' income (Government of India, 2025). The quality of the bulb and productivity of onion are highly impacted by the availability of nutrients and the health of the soil, yet onion is adaptable to a wide range of agro-climatic situations.

This vegetable crop is significant because of its nutritional and nutraceutical attributes. Fresh onion bulbs comprise approximately 86-90% moisture, 8-12% carbs, 1.0-1.5% protein, 1.5-2.0% dietary fibre and minimal fat content. They are abundant in essential minerals such as potassium (146-170 mg 100 g^{-1}), calcium (20-30 mg 100 g^{-1}), phosphorus (25-40 mg 100 g^{-1}), and iron (0.2-0.5 mg 100 g^{-1}), as well as vitamins including vitamin C (7-12 mg 100 g^{-1}), vitamin B_6 (0.1-0.2 mg 100 g^{-1}), and folates, which are vital for human nutrition (Zhao *et al.*, 2021). Moreover, onions are rich in bioactive substances such as flavonoids, phenolic acids, and organosulfur compounds, which exhibit potent antioxidant, anti-inflammatory, antibacterial, and anticancer properties (Sagar *et al.*, 2022). Flavonoids, especially quercetin and its derivatives, augment the antioxidant capacity of onion (Bystrická *et al.*, 2013), whereas sulfur-containing chemicals account for its distinctive pungency and therapeutic attributes. Moreover, quality parameters, including bulb growth, dry matter content, total soluble solids (TSS) and pyruvic acid concentration, are significantly affected by nutrient management strategies, thereby influencing bulb quality, storage longevity, and market acceptability.

Conventional nutrient management practices that rely on excessive chemical fertilizer use have led to declining soil fertility, reduced microbial activity and environmental concerns. In this context, biofertilizers have emerged as sustainable alternatives that improve nutrient availability and soil health. Biofertilizers such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), and sulfur-solubilizing bacteria (SSB) enhance nutrient uptake through biological processes and improve rhizospheric interactions. Their application has been reported to improve growth, yield and quality traits in onion (Singh *et al.*, 2020). They also contribute to improved soil structure and nutrient cycling (Petrovic *et al.*, 2020).

Biostimulants are another important component of sustainable agriculture, consisting of substances or microorganisms that enhance plant physiological processes. These include seaweed extracts, humic substances, amino acids and microbial formulations. Biostimulants improve nutrient use efficiency, enhance stress tolerance, and promote metabolic activity in plants (Vojnović *et al.*, 2023). Their application has been shown to enhance bulb development and overall crop performance (Zhang *et al.*, 2025). In addition, biostimulants play a significant role in mitigating abiotic stresses such as drought and salinity by regulating osmotic balance and antioxidant systems (Hefzy *et al.*, 2020).

Recent research has highlighted the potential of integrating biofertilizers and biostimulants to enhance crop productivity and promote sustainable agriculture. Their combined application improves nutrient use efficiency, reduces dependence on chemical fertilizers and supports environmentally sustainable production. Studies have reported the beneficial effects of integrated nutrient management in onion and other horticultural crops (Mohamed *et al.*, 2022), while microbial-based inputs have also been shown to enhance overall plant performance (Gemin *et al.*, 2022). However, information on the combined use of sulfur-solubilizing bacteria (SSB), phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB) and biostimulants under reduced fertilizer regimes remains limited. Therefore, the present study was undertaken to evaluate "Impact of Integrated Application of Biostimulants and Biofertilizers on Growth Performance of Onion (*Allium cepa* L.)" and to develop sustainable and efficient nutrient management strategies.

Material and Methods

A field experiment was conducted during the late Kharif seasons of 2024-25 and 2025-26 at the Research Farm of the Rajasthan Agricultural Research Institute (RARI), Durgapura, Jaipur, Rajasthan. The experimental site falls under Agro-Climatic Zone III-A (Semi-Arid Eastern Plain) of Rajasthan and is geographically located at 26.5° N latitude and 75.47° E longitude, at an altitude of 390 m above mean sea level. The region experiences a semi-arid climate characterized by hot summers, cool winters, low and erratic rainfall, and moderate relative humidity. The average annual rainfall is approximately 500 mm, most of which is received during July to early September, with occasional winter showers. The maximum temperature during May and June ranges from 28 to 45°C, while the minimum temperature during December and January may fall below 3°C. The evaporation rate varies from 1.3 to 17.5 mm day^{-1}. Meteorological observations were recorded during the experimental period at the Meteorological Observatory of RARI, Durgapura, Jaipur. The experiment was conducted using the onion cultivar 'Bhima Super' under recommended agronomic practices to evaluate the effect of integrated application of biostimulants and biofertilizers during the late *Kharif* season.

Plant Analysis

The chlorophyll content in onion leaves at 60 days after transplanting was estimated following the method of Arnon (1949). Fresh leaf samples (50 mg) were ground in 10 ml of 80% acetone to extract chlorophyll. The homogenate was centrifuged at 2000 rpm for 10 minutes and the final volume of the supernatant was adjusted to 10 ml with 80% acetone. The absorbance of the clear supernatant was measured at 652 nm using a Spectronic 20 spectrophotometer. The chlorophyll content was calculated and expressed as mg per g of fresh leaf weight.

The total chlorophyll content was calculated using the formula:

$$Total\ chlorophyll\ (mg/g) = \frac{A_{652} \times 29 \times Total\ volume\ (ml)}{\alpha \times 1000 \times Weight\ of\ sample\ (g)}$$

Treatment details

The experiment was conducted in a split-plot design with three replications, comprising 24 treatment combinations. The main plot consisted of six foliar biostimulant treatments, viz., A_1: 100% RDF (100:50:50 kg $N:P_2O_5:K_2O$ ha^{-1}), A_2: 75% RDF + Ascophyllum extract (4%), A_3: 75% RDF + Moringa leaf extract (4%), A_4: 75% RDF + Potassium humate (0.2%), A_5: 75% RDF + Ascophyllum extract (4%) + Moringa leaf extract (4%) + Potassium humate (0.2%), and A_6: 50% RDF + Ascophyllum extract (4%) + Moringa leaf extract (4%) + Potassium humate (0.2%). The sub-plot comprised four soil application treatments of biofertilizers, viz., B_1: Control, B_2: SSB + PSB + KSB each @ 0.25 g m^{-2}, B_3: SSB + PSB + KSB each @ 0.35 g m^{-2} and B_4: SSB + PSB + KSB each @ 0.45 g m^{-2}.

Statistical analysis

The experimental data were subjected to statistical analysis using the Analysis of Variance (ANOVA) appropriate for a split-plot design, as described by Cochran and Cox (1957). The total variation was partitioned into two components: main-plot and subplot effects.

Results and Discussion

Plant Height at 40, 60 and 80 DAT (cm)

Plant height (cm)

The data presented in Table 4.1 revealed that plant height at 40, 60 and 80 DAT was significantly influenced by different biostimulant and biofertilizer treatments during both years and in the pooled analysis. Among the biostimulant treatments, A_5 (75% RDF + 4% *Ascophyllum* extract + 4% moringa leaf extract + 0.2% potassium humate) recorded the maximum plant height during 2024-25 (40.19, 50.34 and 65.95 cm), 2025-26 (40.69, 51.48 and 67.02 cm) and in the pooled analysis (40.43, 50.91 and 66.48 cm at 40, 60 and 80 DAT, respectively). Treatment A_5 remained significantly superior to all other treatments at 40 DAT, while it was statistically at par with A_1 at 60 DAT during both years and at 80 DAT during 2024-25. The lowest plant height was consistently recorded under A_6. Among the biofertilizer treatments, B_4 (SSB + PSB + KSB each @ 0.45 g m^{-2}) recorded the highest plant height (36.30, 45.27 and 59.59 cm in 2024–25; 37.03, 46.26 and 60.86 cm in 2025-26; and 36.66, 45.76 and 60.22 cm in the pooled analysis at 40, 60 and 80 DAT, respectively), remaining statistically at par with B_3, whereas the control (B_1) recorded the lowest values.

The improved plant height under A_5 may be attributed to the synergistic effect of *Ascophyllum* extract, moringa leaf extract and potassium humate applied along with reduced RDF, which likely enhanced nutrient availability, photosynthetic efficiency and overall metabolic activity. Similarly, the superior performance of B_4 could be due to enhanced nutrient solubilization, greater nutrient uptake and increased rhizosphere microbial activity. These findings corroborate the reports of Leni *et al.* (2022) and Biswas *et al.* (2024), who observed significant improvements in onion growth following the integrated application of seaweed-based biostimulants. Likewise, Reddy *et al.* (2025) reported enhanced vegetative growth with seaweed and moringa leaf extracts, while Vojnović *et al.* (2023) and Anandakumar *et al.* (2025) attributed the growth-promoting effects of seaweed- and humic substance-based biostimulants to improved physiological processes and nutrient utilization.

Number of Leaves

Number of leaves per plant

Effect of Biostimulants

The data presented in Table 4.2 revealed that the number of leaves per plant was significantly influenced by different biostimulant treatments during both years and in the pooled analysis. During 2024-25, treatment A_5 recorded the highest number of leaves per plant (12.77), which was statistically at par with A_1 (12.34) and significantly superior to the remaining treatments. Treatment A_3 recorded 11.18 leaves per plant, whereas the minimum (8.24) was observed under A_6, representing a 54.98% increase under A_5 over A_6. A similar trend was observed during 2025-26, where A_5

produced the maximum number of leaves (12.42), remaining statistically at par with A_1 (12.03), while A_3 and A_6 recorded 11.27 and 8.11 leaves per plant, respectively, with a 53.14% increase over A_6. The pooled analysis further confirmed the superiority of A_5, which recorded the highest number of leaves per plant (12.59), followed by A_1 (12.18), both being statistically at par. Treatment A_3 recorded 11.22 leaves per plant, whereas A_6 consistently recorded the lowest value (8.17). Overall, A_5 increased the pooled number of leaves per plant by 54.10% over A_6. The enhanced leaf production under A_5 may be attributed to the synergistic effect of *Ascophyllum* extract, moringa leaf extract and potassium humate, which improved nutrient availability, photosynthetic activity and cell division, thereby promoting vegetative growth. These findings are in agreement with Samanta *et al.* (2024), who reported improved vegetative growth in onion following seaweed extract application, Kanchani and Harris (2019), who observed increased leaf production with moringa leaf extract, and Kumar *et al.* (2025), who reported enhanced onion growth following humic acid application.

Effect of Biofertilizers

Biofertilizer treatments also exerted a significant influence on the number of leaves per plant during both years and in the pooled analysis (Table 4.2). During 2024-25, treatment B_4 recorded the highest number of leaves (10.88), remaining statistically at par with B_3 (10.68), whereas the control (B_1) recorded the lowest value (9.89), resulting in a 10.01% increase under B_4. During 2025-26, B_4 again produced the maximum number of leaves (10.52), which was statistically at par with B_3 (10.52), while the minimum (9.58) was observed under B_1, showing a 9.81% increase over the control. The pooled analysis followed the same trend, with B_4 recording the highest number of leaves (10.60), statistically comparable with B_3 (10.60), whereas B_1 registered the lowest pooled value (9.73). Overall, B_4 improved the pooled number of leaves per plant by 8.94% over the control. The improvement in leaf production under higher biofertilizer application may be attributed to enhanced nutrient solubilization, increased nutrient uptake and improved rhizospheric microbial activity. These findings corroborate those of Sundharaiya *et al.* (2016) and Abdissa *et al.* (2011), who reported increased vegetative growth in onion with integrated nutrient management, while Sahoo *et al.* (2012) and Kiruba and Saeid (2022) attributed such responses to improved nutrient availability and beneficial microbial activity associated with biofertilizer application.

Leaf length (cm)

Effect of Biostimulants

The data presented in Table 4.3 revealed that leaf length was significantly influenced by different biostimulant treatments during both years of experimentation and in the pooled analysis. During 2024-25, treatment A_5 recorded the maximum leaf length (61.95 cm), which remained statistically at par with A_1 (58.47 cm), whereas the minimum (42.07 cm) was observed under A_6, representing a 47.25% increase over A_6. A similar trend was observed during 2025-26, where A_5 produced the longest leaves (62.57 cm), remaining statistically at par with A_1 (59.29 cm), while A_6 recorded the lowest value (42.25 cm), with a 48.09% increase over A_6. The pooled analysis further confirmed the superiority of A_5, which recorded the highest leaf length (62.25 cm) and was significantly superior to A_1 (58.88 cm), whereas A_6 registered the minimum pooled value (42.16 cm). Overall, A_5 increased pooled leaf length by 47.65% over A_6. The improved leaf growth under A_5 may be attributed to the synergistic effect of *Ascophyllum* extract, moringa leaf extract and potassium humate, which enhanced nutrient utilization and physiological activity. These findings are in agreement with Thirumalesh *et al.* (2025), Marey and Elmasry (2024), Muhie *et al.* (2020) and Hegazi *et al.* (2016), who reported enhanced vegetative growth following the application of seaweed extract and moringa leaf extract.

Effect of Biofertilizers

Biofertilizer treatments significantly affected leaf length during both years and in the pooled analysis (Table 4.3). During 2024-25, treatment B_4 recorded the maximum leaf length (55.59 cm), remaining statistically at par with B_3 (54.88 cm), whereas the control (B_1) recorded the minimum value (49.51 cm), resulting in a 12.28% increase under B_4. During 2025-26, B_4 again produced the longest leaves (56.26 cm), which was statistically comparable with B_3 (55.28 cm), while B_1 recorded the lowest leaf length (49.66 cm), with a 13.29% increase over the control. The pooled analysis followed the same trend, with B_4 recording the highest leaf length (55.92 cm), remaining statistically at par with B_3 (55.08 cm), whereas B_1 registered the lowest pooled value (49.58 cm). Overall, B_4 improved pooled leaf length by 12.79% over the control. The enhanced leaf length under higher biofertilizer application could be attributed to improved nutrient solubilization, nutrient uptake and microbial activity in the rhizosphere. Similar findings have been reported by Mohamed *et al.* (2022), Mounir *et al.* (2020), Rai *et al.* (2014) and Sajjan Ganiger *et al.* (2025), who observed improved vegetative growth following the application of beneficial microbial inoculants and biofertilizers.

Chlorophyll (mg 100 g^{-1})

Effect of Biostimulants

The chlorophyll content was significantly influenced by different biostimulant treatments during both years and in the pooled analysis (Table 4.X). During 2024–25, treatment A_5 recorded the highest chlorophyll content (5.47 mg/100 g), which was statistically at par with A_1 (5.33 mg/100 g), whereas the lowest value (4.08 mg/100 g) was recorded under A_6, representing a 34.07% increase over A6. A similar trend was observed during 2025-26, where A_5 recorded the maximum chlorophyll content (5.69 mg/100 g), remaining at par with A_1 (5.48 mg/100 g), while A_6 recorded the minimum value (4.10 mg/100 g), showing a 38.78% increase over A6. In the pooled analysis, A_5 recorded the highest chlorophyll content (5.57 mg/100 g) and was significantly superior to A_1 (5.40 mg/100 g), whereas A_6 recorded the lowest value (4.08 mg/100 g). Overall, A_5 increased pooled chlorophyll content by 36.52% over A_6. The enhanced chlorophyll content may be attributed to improved nutrient uptake and photosynthetic efficiency induced by the combined application of biostimulants, corroborating the findings of Mógor *et al.* (2021) and Bahgat *et al.* (2023).

Effect of Biofertilizers

Biofertilizer treatments also significantly influenced chlorophyll content during both years and in the pooled analysis (Table 4.X). During 2024-25, B_4 recorded the highest chlorophyll content (5.00 mg/100 g), which was statistically at par with B_3 (4.87 mg/100 g), whereas the lowest value (4.48 mg/100 g) was recorded under B_1, representing an 11.61% increase over the control. During 2025-26, B_4 again recorded the maximum chlorophyll content (5.21 mg/100 g), remaining at par with B_3 (5.11 mg/100 g), while B_1 recorded the minimum value (4.65 mg/100 g), with a 12.04% increase over the control. In the pooled analysis, B_4 recorded the highest chlorophyll content (5.21 mg/100 g), significantly superior to B_3 (4.99 mg/100 g), whereas B_1 recorded the lowest value (4.56 mg/100 g). Overall, B_4 increased pooled chlorophyll content by 14.25% compared with the control. The increased chlorophyll content is consistent with the findings of RM and Rashwan (2021).

Table 1: Effect of Biostimulants and Biofertilizers on Plant Height (cm) at 40,60 and 80 Days after Transplanting (DAT)

Treatments	Plant Height (cm) at 40 DAT			Plant Height (cm) at 60 DAT			Plant Height (cm) at 80 DAT		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
A. Main Plot (Foliar spray of Biostimulants)									
A_1	38.27	37.88	38.07	47.63	48.13	47.88	62.22	63.11	62.66
A_2	34.33	35.10	34.71	42.66	43.19	42.92	56.07	56.70	56.387
A_3	36.23	36.80	36.51	44.95	45.35	45.15	59.36	60.06	59.70
A_4	31.11	32.08	31.59	39.51	40.15	39.82	52.25	53.11	52.67
A_5	40.19	40.69	40.43	50.34	51.48	50.91	65.95	67.02	66.48
A_6	26.60	27.39	26.99	34.72	36.29	35.50	46.07	48.27	47.17
S.Em ±	0.97	0.79	0.62	1.24	1.08	0.82	1.63	1.50	1.10
CD(P = 0.05)	3.07	2.50	1.85	3.91	3.40	2.42	5.14	4.71	3.26
B. Sub Plot (Soil application of Biofertilizers)									
B_1	32.02	32.56	32.28	40.42	41.25	40.83	53.34	54.34	53.83
B_2	33.97	34.58	34.27	42.57	43.47	43.02	56.13	56.91	56.51
B_3	35.53	35.80	35.66	44.94	45.42	45.18	58.88	60.09	59.48
B_4	36.30	37.03	36.66	45.27	46.26	45.76	59.59	60.86	60.22
S.Em ±	0.59	0.56	0.40	0.74	0.74	0.52	0.97	0.98	0.68
CD(P = 0.05)	1.69	1.60	1.14	2.12	2.12	1.47	2.78	2.80	1.94

Table 2: Effect of Biostimulants and Biofertilizers on Number of leaves per plant, Leaf length(cm) and Chlorophyll (mg 100 g^{-1}).

Treatments	Number of leaves per plant			Leaf length (cm)			Chlorophyll (mg 100 g^{-1})		
	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled	2024-25	2025-26	Pooled
A. Main Plot (Foliar spray of Biostimulants)									
A_1	12.34	12.03	12.18	58.47	59.29	58.88	5.33	5.48	5.40
A_2	9.65	9.43	9.53	52.07	52.36	52.21	4.47	4.86	4.66
A_3	11.18	11.27	11.22	55.36	55.88	55.62	4.91	5.22	5.06
A_4	8.56	8.48	8.52	48.25	48.21	48.22	4.26	4.42	4.34

A_5	12.77	12.42	12.59	61.95	62.57	62.25	5.47	5.69	5.57
A_6	8.24	8.11	8.17	42.07	42.25	42.16	4.08	4.10	4.08
S.Em ±	0.25	0.25	0.17	1.51	1.54	1.08	0.06	0.07	0.04
CD(P = 0.05)	0.78	0.78	0.51	4.76	4.86	3.18	0.19	0.22	0.13
B. Sub Plot (Soil application of Biofertilizers)									
B_1	9.89	9.58	9.73	49.51	49.66	49.58	4.48	4.65	4.56
B_2	10.37	10.17	10.27	52.13	52.50	52.31	4.65	4.88	4.76
B_3	10.68	10.52	10.60	54.88	55.28	55.08	4.87	5.11	4.99
B_4	10.88	10.86	10.87	55.59	56.26	55.92	5.00	5.21	5.10
S.Em ±	0.18	0.20	0.13	0.90	0.92	0.64	0.05	0.05	0.03
CD(P = 0.05)	0.52	0.58	0.38	2.59	2.64	1.81	0.14	0.15	0.09

Conclusions

The integrated use of biostimulants and biofertilizers substantially enhanced onion growth by improving plant height, leaf length, number of leaves and chlorophyll content. The superior performance of A_5 in combination with B4 highlights the synergistic role of biostimulants and beneficial microorganisms in promoting nutrient use efficiency and photosynthetic capacity. Therefore, the integration of these inputs with 75% RDF represents a promising, sustainable nutrient management approach for improving onion crop performance while minimizing reliance on chemical fertilizers.

Acknowledgement

The author sincerely acknowledges the Director, Rajasthan Agricultural Research Institute (RARI), Durgapura, Jaipur, Rajasthan, for providing the necessary facilities and support to carry out this research. The author also expresses heartfelt thanks to the staff of the Department of Horticulture for their valuable assistance during the conduct of the experiment and data recording. Their cooperation is gratefully acknowledged.

Conflict of interest

The authors declare that they have no conflict of interest.

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