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Impact of irrigation levels and bio-regulators on physiological and yield traits of Indian mustard (*Brassica juncea* L.)

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Abstract
A field experiment was conducted to evaluate the Impact of irrigation levels and bio-regulators on growth and yield attributes of Indian mustard (*Brassica juncea* L.). The experiment comprised three irrigation levels: no post-sowing irrigation (control), one irrigation at 40 days after sowing (DAS) and two irrigations at 40 and 75 DAS along with five bio-regulator treatments: water spray (control), GA_3 @ 50 ppm at 50% flowering stage, Thiourea @ 500 ppm at 50% flowering stage, GA_3 @ 50 ppm at 50% flowering + 50% Pod formation stage and Thiourea @ 500 ppm at 50% flowering + at 50% Pod formation stage. The results revealed that two irrigations at 40 and 75 DAS significantly enhanced plant height, number of branches, dry matter accumulation, yield attributes *viz.*, siliquae plant^{-1}, seeds siliqua^{-1}, siliqua length compared to one irrigation and control. However, application of thiourea @ 500 ppm at 50% flowering + at 50% Pod formation stage outperformed other bio-regulators, showing significant improvement in growth as well as yield attributes. Whereas, statistical analysis indicated that irrigation levels not exerted a significant influence on plant stand and days required to 50% flowering a well as foliar application of bio-regulators did not exert any significant effect on plant stand, test weight and days required to 50% flowering and maturity.

Keywords: Growth, development, phenology, Integrated Nutrient Management (INM) and Barley

Introduction
India is a leading global producer of oilseeds, especially Brassica crops like *Brassica juncea*, ranking fourth in the vegetable oil economy after the USA, China, and Brazil. Indian mustard, a key rabi oilseed mainly grown in northern India, contributes significantly to production and is locally known as sarson, Shorshe, Rai, Mohari, Aavalu, Kadugu, and Sasive. Oilseed cultivation (27 million ha) is largely rainfed (72%), making yields sensitive to erratic rainfall and limited irrigation. Globally, major mustard producers include China, India, Canada, Australia, France, and Germany. In India, mustard is grown across Rajasthan, Uttar Pradesh, Haryana, Madhya Pradesh, and Gujarat, with Rajasthan leading (45.5% of area), followed by Uttar Pradesh (13.1%), Haryana (11.8%), and Madhya Pradesh (11.1%). During 2023-24, Indian mustard was cultivated on 6.23 million hectares, producing 13.2 million tonnes at an average productivity of 1499 kg/ha. Rajasthan contributed the largest share with 3.75 million hectares and 6.23 million tonnes, achieving a higher productivity of 1661 kg/ha (Anonymous, 2023) [1].
Indian mustard is an economically and nutritionally important oilseed, rich in oil (35-40%), erucic acid (40-57%), protein (25-30%), omega-3 fatty acids, B-complex vitamins, and vitamin E (19.82 mg/100 g). Mustard oil is widely used in cooking and traditional medicine, while the residual oilcake serves as manure or animal feed. Mustard productivity in India, largely rainfed (~90%), is limited by erratic rainfall and inadequate irrigation. Timely supplemental irrigation during critical stages (30-75 DAS) improves growth, seed and oil yield, water use efficiency, economic returns, and oil quality (Tamboli *et al*., 2024; Kumar & Dhillon, 2023; Piri *et al*., 2019; Ray *et al*., 2016) [22, 8, 14, 16]. Plant growth bio-regulators help mitigate moisture stress in

mustard. Thiourea (500 ppm) improves chlorophyll synthesis, enzyme activity, osmotic adjustment, and assimilate translocation, enhancing water use efficiency, seed yield, oil content, and harvest index. Gibberellic acid (GA_3) promotes stem elongation, leaf expansion, seed development, photosynthate translocation, nutrient uptake, and stress tolerance, improving yield and oil quality (Sumi *et al*., 2021) [21]. Integrating bio-regulators with timely irrigation enhances crop resilience and productivity under water-limited conditions, providing an effective strategy for improving mustard performance in India.

Materials and Methods

Experimental Site

The experiment was conducted at the Research Farm, School of Agricultural Sciences, Jaipur National University, Jaipur (26°85' N, 75°87' E; 390 m AMSL), located in Rajasthan's NARP agro-climatic zone IIIa (Semi-Arid Eastern Plain Zone).

Weather

The region has a hot semi-arid climate with extreme temperatures and low to moderate rainfall. Summers reach up to 45°C, winters drop to around 5 °C, and annual rainfall averages 527 mm. Humidity ranges from 20-30% in summer to 60-80% in the monsoon, with winds of 5-15 km/h, gusting up to 40 km/h during dust storms. Sunshine lasts 8-10 h in summer, 6-8 h in winter, and 4-6 h during the monsoon. In the 2024-25 rabi season, temperatures ranged from 33.8 °C to 8.6 °C, with occasional rainfall.

Sampling and analyses

The experimental soil is sandy loam of Gangetic alluvial origin (68.14% sand, 22.58% silt, 9.28% clay) with an alkaline pH of 7.74, low organic carbon (0.41%), moderate nitrogen (133.26 kg/ha) and phosphorus (19.89 kg/ha), and high potassium (231.19 kg/ha). Its physical properties include bulk density 1.52 Mg/m^3, particle density 2.53 Mg/m^3, and porosity 39.92%. Soil analyses for texture, pH, conductivity, and nutrients were performed using standard methods. The procedures used were based on Piper (1950) [13] and Black (1950) [2], Olsen *et al*. (1954) [11], Richards (1954) [17], Subbaiah and Asija (1956) [20] and Jackson (1973) [7].

Experimental setup

A field experiment was conducted to evaluate the Impact of irrigation levels and bio-regulators on growth, yield and WUE of Indian mustard (*Brassica juncea* L.). The experiment comprised three irrigation levels: no post-sowing irrigation (control), one irrigation at 40 days after sowing (DAS) and two irrigations at 40 and 75 DAS along with five bio-regulator treatments: water spray (control), GA_3 @ 50 ppm at 50% flowering stage, Thiourea @ 500 ppm at 50% flowering stage, GA_3 @ 50 ppm at 50% flowering + 50% Pod formation stage and Thiourea @ 500 ppm at 50% flowering + at 50% Pod formation stage. The field was prepared and fertilizers were applied: 60 kg N, 30 kg P_2O_5, 5 kg $ZnSO_4$, and 40 kg S/ha (as gypsum). Full doses of P, Zn, and S were applied at sowing, while N was split-half at sowing and half after the first irrigation, using urea (46% N) and DAP (46% P_2O_5, 18% N) as sources. All necessary agronomic practices were followed to ensure optimal crop growth and development. Observations were made from five randomly selected plants in each plot to assess various growth and yield attributes and dry matter from the gross plot. Additionally, the number of days from sowing to 50% flowering and physiological maturity was recorded. Statistical analysis was conducted for each character based on the experimental design, and the simple correlation coefficient ('r') for each character was calculated as per Gomez and Gomez (1984) [5].

Results and Discussion

Data presented in Table 1, 2 and 3 indicate that different irrigation levels and bio-regulator treatments significantly enhanced the growth parameters *viz.* plant height (cm), number of primary and secondary branches per plant and dry matter accumulation (g) at 30, 60, 90 DAS and at harvest, respectively as well as number of siliquae per plant, number of seeds per siliqua, length of siliqua and test weight.

Effect Irrigation

Growth and Phenological Parameters

The plant stands at 20 DAS and at harvest showed no significant variation among treatments, although a slight decline was observed as the crop matured (Table 1). Days to 50% flowering were also unaffected by irrigation levels (Table 4.5). Plant height increased progressively with crop age, with faster growth up to 90 DAS, and was significantly influenced by irrigation and bio-regulators at 60, 90 DAS, and harvest (Table 4.2, Figure 3). Two irrigations at 40 and 75 DAS (I_3) produced the tallest plants (128.70, 154.34, 158.58 cm at 60, 90 DAS, and harvest) and was statistically similar to one irrigation at 40 DAS (I_2) at 60 DAS, while the control (I_1) consistently recorded the shortest plants. At harvest, I_3 significantly increased both primary (6.01) and secondary branches (14.48) per plant compared to I_2 and I_1 (Table 4.3, Figure 4), producing 16.92% more primary and 23.02% more secondary branches than I_2, and 33.85% more primary and 32.60% more secondary branches than I_1. Dry matter accumulation was highest under I_3 (34.08, 80.00, and 103.55 g $plant^{-1}$ at 60, 90 DAS, and harvest), superior to I_2 and the control at all stages, and statistically similar to I_2 only at harvest. I_3 also resulted in the longest duration to physiological maturity (124.70 days), similar to I_2, while the shortest duration was recorded in the control (I_1).

Adequate soil moisture through irrigation or rainfall promotes photosynthetic activity and overall plant growth. The treatment with two irrigations at 40 and 75 DAS (I_3) ensured better turgidity, enhanced meristematic activity, and greater foliage development, resulting in improved nutrient uptake, higher photosynthetic efficiency, and increased dry matter accumulation. In contrast, moisture deficits under I_1 (no irrigation) and I_2 (one irrigation) caused reduced turgor and inhibited growth processes. Application of two irrigations (I_3) also prolonged the period to physiological maturity compared to the control (I_1), which matured earlier due to limited moisture and nutrient uptake. Similar findings were reported by Tamboli *et al.* (2023) [23] and Tamboli *et al.* (2024) [22].

Yield attributes

The number of siliquae per plant, seeds per siliqua, siliqua length, and test weight all increased with higher irrigation levels (Table 3 and Figure 2). Two irrigations at 40 and 75 DAS (I_3) produced the highest values: 202.50 siliquae per plant (7.29% more than I_2, 21.29% more than I_1), 16.87 seeds per siliqua (7.24% over I_2, 21.89% over I_1), siliqua length 5.93 cm (2.24% over I_2, 18.83% over I_1), and test weight 6.09 g (21.31% over I_2, 28.48% over I_1). These parameters under I_3 were statistically similar to one irrigation at 40 DAS (I_2) in some cases, while the control (I_1) consistently recorded the lowest values. The superior performance under I_3 can be attributed to improved cell turgidity, enhanced stomatal conductance, and increased photosynthetic activity, which promoted greater leaf expansion, higher leaf area, and efficient dry matter partitioning among plant parts. In contrast, moisture stress under I_1 reduced turgor-driven physiological processes such as stomatal conductance, photosynthesis, and leaf expansion, leading to lower leaf area duration, reduced absorption of photosynthetically active radiation (PAR), and ultimately decreased crop growth and yield attributes. These results are in close agreement with the findings of Hossain *et al.* (2013) [6], Tamboli *et al.* (2023) [23] and Tamboli *et al.* (2024) [22].

Effect of bio-regulators

Growth and Phenological Parameters

Plant stand recorded at 20 DAS and at harvest showed no significant variation among bio-regulator treatments, although a slight decline was observed as the crop matured (Table 1). Plant height was significantly influenced by bio-regulators at all stages except 30 DAS (Table 1, Figure 1). Foliar application of thiourea at 500 ppm at 50% flowering and again at 50% pod formation (B_5) produced the tallest plants (132.09, 149.88, and 153.29 cm at 60, 90 DAS, and harvest), statistically similar to GA_3 at 50 ppm applied at both stages (B_4) and superior to single-stage applications (B_2, B_3) and control (B_1). At harvest, B_5 also produced the highest number of primary (5.77) and secondary branches (13.70) per plant (Table 2), showing 10-15% and 3.86-24.88% increases over other treatments, respectively. Dry matter accumulation at 30, 60, 90 DAS, and harvest was highest under B_5 (77.54 g at 90 DAS; 99.78 g at harvest), statistically similar to B_4 and superior to B_2, B_3, and B_1 (Table 2, Figure 1). Foliar application of bio-regulators had no significant effect on the time required to reach 50% flowering. Foliar application of thiourea @ 500 ppm at 50% flowering and 50% pod formation significantly improved plant height, dry matter accumulation, and branching. This enhancement is attributed to improved nitrogen metabolism, chlorophyll content, enzymatic activity, and cytokinin-like stimulation, promoting photosynthesis and cell division (Chakrabarti *et al*., 2011 [3]; Ghosh *et al*., 2019 [4]; Meena *et al*., 2020 [10]). The effect was comparable to GA_3 @ 50 ppm at the same stages, indicating a physiological threshold beyond which no further growth response occurs (Yadav *et al*., 2022 [25]). However, GA_3 mainly promotes apical dominance, which can limit branching, while thiourea improved source-sink balance and assimilate partitioning (Pandey *et al*., 2010 [12]; Singh, 2020 [19]).

Yield attributes

The data in Table 3 and illustrated in Figure 2 show that the number of siliquae per plant and seeds per siliqua at harvest were significantly influenced by different bio-regulator treatments. The highest values 195.74 siliquae per plant and 16.87 seeds per siliqua were recorded with foliar application of thiourea at 500 ppm at 50% flowering and again at 50% pod formation (B_5), which was statistically at par with GA_3 at 50 ppm applied at both stages (B_4). These were followed by thiourea at 500 ppm at 50% flowering alone (B_3), GA_3 at 50 ppm at 50% flowering alone (B_2), and the control (B_1). Siliqua length at harvest was also significantly influenced by bio-regulator treatments, with the maximum length (5.93 cm) observed under B_5, statistically similar to B_4. The B_5 treatment showed increases of 1.57%, 4.88%, 6.03%, and 8.41% over B_4, B_3, B_2, and B_1, respectively. In contrast, foliar application of bio-regulators had no significant effect on test weight. Foliar application of thiourea @ 500 ppm at 50% flowering and 50% pod formation significantly enhanced seed-setting parameters, including the number of seeds per siliqua, siliqua length, and seed yield per plant, compared to control and GA_3 treatments, though it remained statistically similar to GA_3 @ 50 ppm at the same stages. These improvements are attributed to thiourea's role in maintaining hormonal balance, enhancing photosynthetic efficiency, nitrogen assimilation, and assimilate translocation toward developing pods and seeds (Chakrabarti *et al*., 2011 [3]; Singh, 2020 [19]; Verma *et al*., 2022 [24]; Yadav *et al*., 2022) [25]. In contrast, GA_3 mainly promoted stem elongation with limited reproductive benefits (Saxena *et al*., 2023 [18]). While thiourea markedly improved vegetative and reproductive yield components, test weight and harvest index remained unaffected, indicating that bio-regulators increased overall productivity without altering the proportional distribution of assimilates between seed and stover (Kumawat *et al*., 2021; Rana *et al*., 2023) [9, 15].

Table 2: Plant population (000 ha^{-1}) and Plant height (cm) of Indian mustard as influenced by irrigation levels and bio-regulators

Treatments	Plant population (000 ha^{-1})		Plant height (cm)				Phenology Parameters	
	At initial	At maturity	30 DAS	60 DAS	90 DAS	At harvest	Days to taken 50% flowering	Days to taken physiological maturity
Irrigation level (I)								
I_1- Control (No post-sowing irrigation)	210.18	207.93	20.43	117.24	125.61	130.02	41.03	111.78
I_2-One irrigation at 40 DAS (At pre-bloom stage)	213.98	211.77	20.77	126.26	142.24	147.81	41.71	119.28
I_3-Two irrigations at 40 and 75 DAS (At pre-bloom + pod filling stage)	218.10	216.75	21.01	128.70	154.34	158.58	42.19	124.70
S.Em±	2.54	3.23	0.51	2.92	3.22	2.95	1.03	3.18
CD (5%)	NS	NS	NS	10.10	11.15	10.22	NS	11.00
CV	3.57	4.57	7.43	7.00	6.87	6.09	7.43	8.04
Bio-regulators (B)								
B_1-Control (Water spray)	217.99	215.02	20.50	114.13	128.90	135.80	41.16	116.99
B_2-GA_3 @ 50 ppm at 50% flowering stage	211.57	210.47	20.68	122.63	136.71	142.92	41.52	118.05
B_3-Thiourea @ 500 ppm at 50% flowering stage	209.69	208.30	20.82	124.55	140.42	144.40	41.80	118.87
B_4-GA_3 @ 50 ppm at 50% flowering + 50% Pod formation stage	213.22	211.68	20.96	131.93	147.76	150.95	42.09	118.62
B_5-Thiourea @ 500 ppm at 50% flowering + at 50% Pod formation stage	217.97	215.29	20.74	132.09	149.88	153.29	41.64	120.42
S.Em±	2.68	2.32	0.34	2.22	2.45	2.13	0.67	1.92
CD (5%)	NS	NS	NS	6.60	7.29	6.33	NS	NS
CV	4.85	4.23	6.27	6.88	6.75	5.67	6.27	6.03

Table 2: Number of branches per plant at harvest and Dry matter accumulation (g plant^{-1}) of Indian mustard as influenced by irrigation levels and bio-regulators

Treatments	Number of branches per plant at harvest		Dry matter accumulation (g plant^{-1})			
	Primary	Secondary	30 DAS	60 DAS	90 DAS	At harvest
Irrigation level (I)						
I_1- Control (No post-sowing irrigation)	4.49	10.92	3.19	30.85	64.98	83.21
I_2-One irrigation at 40 DAS (At pre-bloom stage)	5.14	11.77	3.25	33.80	73.73	95.88
I_3-Two irrigations at 40 and 75 DAS (At pre-bloom + pod filling stage)	6.01	14.48	3.28	34.08	80.00	103.55
S.Em±	0.11	0.46	0.09	0.69	1.72	2.10
CD (5%)	0.40	1.58	NS	2.40	5.95	7.28
CV	6.60	11.02	8.02	6.31	7.08	6.70
Bio-regulators (B)						
B_1-Control (Water spray)	4.99	10.97	3.20	29.67	66.84	87.33
B_2-GA_3 @ 50 ppm at 50% flowering stage	5.03	11.97	3.23	32.27	70.98	92.39
B_3-Thiourea @ 500 ppm at 50% flowering stage	5.06	12.12	3.25	32.78	72.63	93.45
B_4-GA_3 @ 50 ppm at 50% flowering + 50% Pod formation stage	5.23	13.19	3.27	35.08	76.52	98.11
B_5-Thiourea @ 500 ppm at 50% flowering + at 50% Pod formation stage	5.77	13.70	3.24	34.76	77.54	99.78
S.Em±	0.12	0.40	0.05	0.58	1.25	1.52
CD (5%)	0.36	1.19	NS	1.72	3.72	4.51
CV	9.11	12.53	6.26	6.83	6.66	6.24

Table 3: Number of siliquae per plant, number of seeds per siliqua, length of siliqua, test weight (g) and seed yield per plant (g) of Indian mustard as influenced by irrigation levels and bio regulators

Treatments	Number of Siliqua per plant	Number of Seeds per siliqua	Length of siliqua (cm)	Test weight (g)	Seed yield per plant (g)
Irrigation level (I)					
I_1- Control (No post-sowing irrigation)	166.02	13.84	4.99	4.74	15.11
I_2-One irrigation at 40 DAS (At pre-bloom stage)	188.74	15.73	5.80	5.02	18.09
I_3-Two irrigations at 40 and 75 DAS (At pre-bloom + pod filling stage)	202.50	16.87	5.93	6.09	19.78
S.Em±	3.77	0.31	0.09	0.12	0.46
CD (5%)	13.05	1.09	0.29	0.43	1.60
CV	6.09	6.09	4.58	7.07	7.86
Bio-regulators (B)					
B_1-Control (Water spray)	173.41	14.45	5.35	4.70	16.15
B_2-GA_3 @ 50 ppm at 50% flowering stage	182.49	15.21	5.47	5.34	17.26
B_3-Thiourea @ 500 ppm at 50% flowering stage	184.39	15.37	5.53	5.36	17.49
B_4-GA_3 @ 50 ppm at 50% flowering + 50% Pod formation stage	192.75	16.06	5.71	5.46	18.52
B_5-Thiourea @ 500 ppm at 50% flowering + at 50% Pod formation stage	195.74	16.31	5.80	5.55	18.89
S.Em±	2.72	0.23	0.07	0.16	0.33
CD (5%)	8.08	0.67	0.20	NS	0.99
CV	5.67	5.67	4.70	11.83	7.32

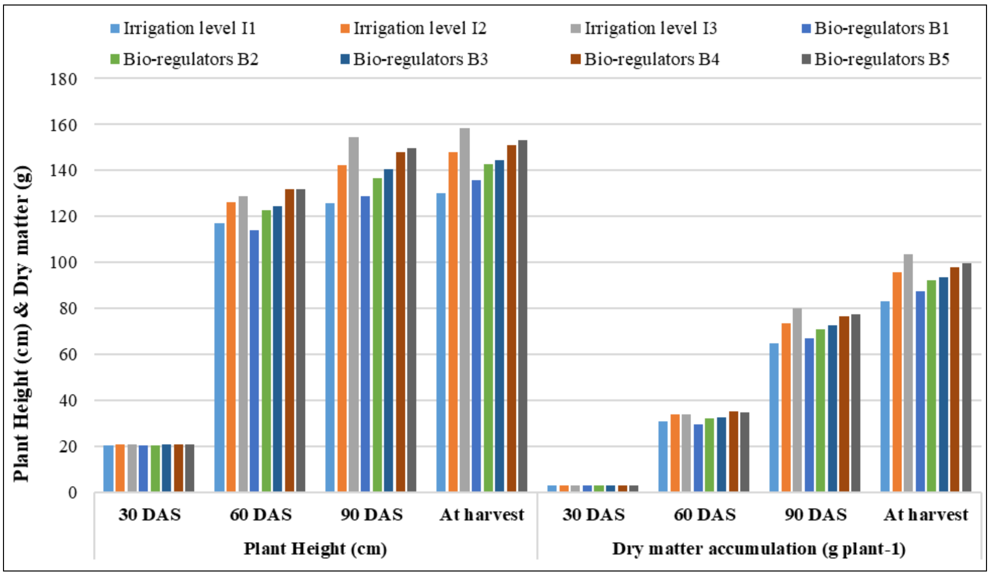

Fig 1: Plant height and Dry matter accumulation (g plant^{-1}) of Indian mustard as influenced by irrigation levels and bio-regulators

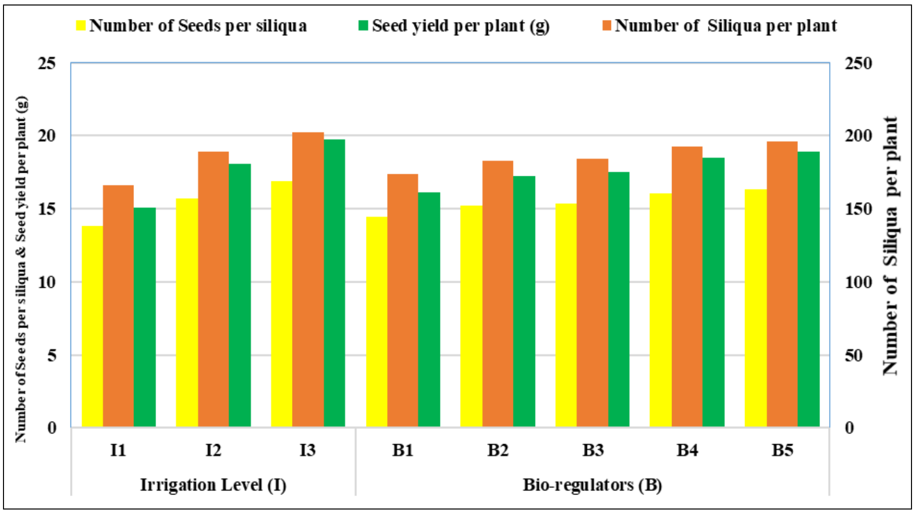

Fig 2: Number of siliquae per plant, seeds per siliqua and seed yield per plant (g) of Indian mustard as influenced by irrigation levels and bio regulators

Conclusion

Based on this one-year study, it can be concluded that two irrigations at critical growth stages (40 and 75 DAS) significantly improved the growth, yield attributes, and overall productivity of Indian mustard, highlighting the importance of timely irrigation under local agro-climatic conditions. Foliar application of thiourea @ 500 ppm at 50% flowering and 50% pod formation further enhanced growth and yield by improving nitrogen metabolism, antioxidant activity, and stress tolerance. The combined use of two irrigations with thiourea @ 500 ppm proved to be the most effective approach for maximizing the growth and productivity of Indian mustard on loamy sand soils in Jaipur's agro-climatic zone.

Future Prospects

Future research could focus on multi-year and multi-location trials to validate the effectiveness of combined irrigation and thiourea application under varying agro-climatic conditions. Exploring the integration of other bio-regulators, optimized irrigation schedules, and nutrient management strategies may further enhance yield, water use efficiency and stress resilience in Indian mustard. Additionally, studies on the physiological and molecular mechanisms underlying thiourea-mediated growth and stress tolerance could provide insights for precision agronomy and sustainable mustard cultivation.

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