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Response of mustard to varying levels of irrigation and nitrogen

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Abstract
A field experiment was led during the Rabi season of 2024-25 at SAGE Instructional &Research form, School of Agriculture, SAGE University, Bhopal, M.P. to evaluate the effects of irrigation levels and nitrogen doses, with and without mulch, on Indian mustard (*Brassica juncea*). The study used a Factorial Randomized Block Design with 18 treatment combinations: three irrigation levels (0, 1, and 2 irrigations), three nitrogen levels (60, 90, and 120 kg/ha), and two mulching treatments. Results revealed that two irrigations at branching and flowering, combined with 120 kg N/ha and mulch, significantly enhanced plant growth, yield attributes, seed yield, water use efficiency (WUE), and net returns. Mulching improved soil moisture, reduced weed growth, and increased nutrient efficiency. The integrated application of irrigation, nitrogen, and mulch proved to be the most effective strategy under semi-arid conditions, promoting sustainable and profitable mustard production. The study recommends this integrated approach for maximizing productivity, with potential for broader adoption across varied agro climatic zones.

Keywords: Irrigation levels, nitrogen doses, mulching, mustard productivity and WUE

Introduction
Mustard (*Brassica juncea*) is one of the most significant oilseeds crops globally, with its cultivation expanding due to rising demand for edible oils. In 2023, India emerged as the world's leading producer of mustard seed, contributing approximately 12 million tonnes. During the 2023-24 rabi season, the country achieved a record production of 120.9 lakh tonnes, cultivated over an estimated 100.6 lakh hectares, resulting in an average yield of 1,201 kg/ha.

Among the leading mustard-producing states, Madhya Pradesh made a substantial contribution. The state recorded a production of nearly 17.6 lakh tonnes, with about 13.98 lakh hectares under mustard cultivation, yielding an average of 1,258 kg/ha. Given its consistent output, Madhya Pradesh holds a strategic position in India's oilseed economy, making it a priority region for agronomic advancements. Mustard (*Brassica spp.*) is cultivated widely across a range of agro-climatic zones, particularly thriving in dry and semi-dry regions where water shortages and soil fertility constraints often hinder crop productivity. As the global emphasis on sustainable agriculture and edible oil production intensifies, improving the efficiency of resource utilization in mustard farming becomes increasingly important. Among the key agronomic factors, irrigation and nitrogen management play crucial roles in influencing the crop's growth, yield potential, and quality. Inadequate water availability during critical growth stages can severely restrict plant development and seed formation. Likewise, inefficient nitrogen use can result in poor nutrient absorption, decreased yields, and adverse environmental effects.

Mulching, on the other hand, has gained prominence for its role in conserving soil moisture, moderating soil temperature, reducing weed growth, and improving nutrient retention. Its integration into crop management could significantly influence how mustard responds to both irrigation and nutrient application. However, while each of these practices—irrigation, nitrogen management, and mulching—has demonstrated individual benefits, there is limited research on their combined or interactive effects on mustard performance, especially under the resource-constrained conditions prevalent in regions like Madhya Pradesh.

This research is therefore designed to investigate the response of mustard to different irrigation and nitrogen levels, with and without the application of mulch. The objective is to identify the most effective combinations that can maximize yield, enhance resource-use efficiency, and promote environmentally sustainable practices. The outcomes of this study are expected to support the development of integrated crop management strategies suitable for diverse growing conditions.

Materials and Methods

A field experiment entitled "Response of mustard to levels of irrigation and nitrogen with and without mulch" was conducted during Rabi season of 2024-25. The details of experimental techniques followed, material used and criteria adopted for treatment evaluation during the course of investigation are described in this chapter under appropriate headings. The experiment was laid out at the SAGE Agriculture field, School of Agriculture, SAGE University, Bhopal, Madhya Pradesh, The experimental site is situated geographically at 23°16' N latitude and 77°36' E longitude, with an elevation of 500 meters above sea level. The experiment was designed using a Randomized Block Design, resulting in main treatments 2 and sub treatments 4 each replicated three times. Observations to be recorded on mustard crop plant populationm2, plant height(cm.) number of branched per plant (Primary and secondary) Dry matter accumulation, Number of siliques per plant, Number of seeds silique, 100 seed weight (g.) Biological yield (kg $plot^{-1}$), Seed yield (kg $plot^{-1}$) and Harvest index (%). Experimental data were analysed using analysis of variance (ANOVA) as per randomized block design (RBD). The significance of the treatments was tested using F test with 5% level of significance ($p<0.05$) and means were compared using the critical difference (CD) test at $\alpha = 0.05$. MS Excel 2013 was used to analyse the experimental data for its test of significance.

Result and Discussions

Growth attributes: Growth attributes of mustard, *i.e.* plant population, plant height, dry matter accumulation, number of branches (primary and secondary) were recorded at 30, 60, 90 days (DAS) and at harvest.

Plant population: The plant population at 30 DAS and at harvest was not significantly affected by irrigation levels, nitrogen levels, or their interaction. However, a higher plant population (8.6 plants/m² at 30 DAS and 8.4 plants/m² at harvest) was observed under 0.09 IW/CPE with mulch compared to 0.06 IW/CPE without mulch. Among the nitrogen levels, 125% RDN resulted in the highest plant population (8.8 plants/m² at 30 DAS and 8.6 plants/m² at harvest) Table 1, although these differences were not statistically significant. This suggests that the early establishment and final stand density of plants were not markedly influenced by irrigation level or mulching practices, corroborating findings by Jha, A., & Kumar, S. (2024) [2].

Table 1: Effect on irrigation and nitrogen with and without mulch on plant population at 30 days and at harvest.

Treatments	Plant population(m2)	
	30 DAS	At harvest
Irrigation 0.06 without Mulch	8.5	8.3
Irrigation 0.09 with Mulch	8.6	8.4
SEm±	0.03	0.03
CD (P=0.05)	NS	NS
Nitrogen Level (RDN)		
(RDN50 %)	8.2	8.0
(RDN 75 %)	8.5	8.3
(RDN 100 %)	8.6	8.4
(RDN125 %)	8.8	8.6
SEm±	0.04	0.05
CD (P=0.05)	0.14	0.16
(Factor I × M)	NS	NS

Effect of Irrigation Levels on Plant Height: Plant height was significantly influenced by irrigation levels, mulch, and nitrogen application. The treatment with 0.09 IW/CPE combined with mulch produced the tallest plants (141.54 cm), which were notably higher than those under 0.06 IW/CPE without mulch (137.78 cm). As nitrogen levels increased, plant height also showed a consistent rise, with the maximum height (143.66 cm) recorded at 125% RDN, significantly exceeding the plant heights at lower nitrogen levels. The interaction between irrigation and nitrogen levels was significant only at 60 and 90 DAS, but not at 30 DAS or at harvest Table 2. The increase in plant height can be attributed to the adequate moisture availability in the rhizosphere, which created a favourable growth environment. This improved cell elongation, turgidity, stomatal opening, and efficient partitioning of photosynthates to the sink. In contrast, possibly exposing the crop to more moisture stress at various stages of its water requirement.

Table 2: Effect on irrigation and nitrogen with and without mulch on plant height at 30, 60 and 90 days and at harvest.

Treatments	Plant height (cm)			
	30 DAS	60 DAS	90 DAS	At harvest
Irrigation 0.06 without Mulch	17.1	50.6	96.69	137.78
Irrigation 0.09 with Mulch	19.6	50.9	97.59	141.54
SEm±	0.4	0.08	0.06	1.05
CD (P=0.05)	1.5	0.26	0.18	3.21
Nitrogen Level (RDN)				
(RDN50 %)	15.5	49.08	95.34	136.27
(RDN 75 %)	17.0	50.00	96.72	138.26
(RDN 100 %)	18.6	51.30	97.74	140.46
(RDN125 %)	22.3	52.38	98.77	143.66
SEm±	2.1	0.12	0.08	1.48
CD (P=0.05)	0.7	0.37	0.25	4.55
(Factor I × M)	NS	0.53	0.36	NS

Number of branches (Primary): The number of primary branches was significantly affected by irrigation, mulch, and nitrogen levels. Irrigation at 0.09 IW/CPE with mulch recorded significantly higher branches (6.83) at harvest compared to 0.06 IW/CPE without mulch (5.41). An increase in nitrogen levels also resulted in a significant rise in the number of primary branches, with the maximum (7.50) recorded under 125% RDN Table 3. The interaction effect between irrigation and nitrogen levels was non-significant at 30 DAS and harvest, but significant at 60 and 90 DAS. This aligns with findings by Meena *et al.* (2023) [17] Narayan *et al.* (2020) [3], who observed increased branching under higher irrigation and mulch treatments in legumes. Nitrogen application had a significant and positive effect at all stages.

Table 3: Effect on irrigation and nitrogen with and without mulch on Number of branches (Primary) at 30, 60 and 90 days and at harvest.

Treatments	Number of branches (Primary)			
	30 DAS	60 DAS	90 DAS	At harvest
Irrigation 0.06 without Mulch	4.16	4.50	5.75	5.41
Irrigation 0.09 with Mulch	4.83	5.83	6.66	6.83
SEm±	0.10	0.05	0.05	0.18
CD (P=0.05)	0.31	0.18	0.18	0.56
Nitrogen Level (RDN)				
(RDN50 %)	3.50	4.50	5.50	5.16
(RDN 75 %)	4.33	4.66	5.83	5.66
(RDN 100 %)	4.83	5.50	6.50	6.16
(RDN125 %)	5.33	6.00	7.00	7.50
SEm±	0.14	0.08	0.08	0.26
CD (P=0.05)	0.44	0.25	0.25	0.79
(Factor I × M)	NS	0.36	0.36	NS

Number of branches (Secondary): The number of secondary branches was significantly influenced by irrigation, mulch, and nitrogen levels at 60 and 90 DAS, while the effect was non-significant at harvest. Irrigation at 0.09 IW/CPE with mulch produced a higher number of secondary branches (6.50 at 90 DAS) compared to 0.06 IW/CPE without mulch (5.75). A significant increase in secondary branches was also observed with increasing nitrogen levels, with the highest number (7.00 at 90 DAS) 0 1 2 3 4 5 6 7 8 Irrigation 0.06 without Mulch Irrigation 0.09 with Mulch (RDN50 % (RDN 75 % (RDN 100 % (RDN125 % Number of branches (Primary) 30 DAS 60 DAS 90 DAS At harvest 52 recorded under 125% RDN Table 4. The interaction between irrigation and nitrogen levels was significant at 60 and 90 DAS but non-significant at harvest. Nitrogen application showed a positive and significant influence on branch formation.

Table 4: Effect on irrigation and nitrogen with and without mulch on Number of branches (Secondary) at 30, 60 and 90 days and at harvest.

Treatments	Number of branches (Secondary)		
	60 DAS	90 DAS	At harvest
Irrigation 0.06 without Mulch	5.33	5.75	5.58
Irrigation 0.09 with Mulch	6.00	6.50	5.83
SEm±	0.05	0.08	0.11
CD (P=0.05)	0.18	0.24	NS
Nitrogen Level (RDN)			
(RDN50 %)	5.00	5.16	5.00
(RDN 75 %)	5.50	5.83	5.33
(RDN 100 %)	5.66	6.50	5.83
(RDN125 %)	6.50	7.00	6.66
SEm±	0.08	0.11	0.15
CD (P=0.05)	0.25	0.34	0.48
(Factor I × M)	0.36	0.49	NS

Dry matter accumulation: The dry matter accumulation was not significantly affected by irrigation and mulch treatments at any stage of crop growth. However, nitrogen levels showed a significant effect at all stages. The highest dry matter accumulation (27.71 g/plant at harvest) was recorded under 125% RDN, which was significantly superior to lower nitrogen levels Table 5. The interaction between irrigation and nitrogen levels was found to be non-significant at all stages Patel *et al.* (2013) [5].

Table 5: Effect on irrigation and nitrogen with and without mulch on Dry matter accumulation at 30, 60 and 90 days and at harvest.

Treatments	Dry matter accumulation			
	30 DAS	60 DAS	90 DAS	At harvest
Irrigation 0.06 without Mulch	4.62	10.98	20.01	26.10
Irrigation 0.09 with Mulch	4.69	11.78	19.74	26.27
SEm±	0.10	0.24	0.20	0.20
CD (P=0.05)	NS	0.75	NS	NS
Nitrogen Level (RDN)				
(RDN50 %)	4.06	10.10	18.68	24.72
(RDN 75 %)	4.43	11.28	19.43	25.59
(RDN 100 %)	4.70	11.81	19.89	26.71
(RDN125 %)	5.43	12.34	21.51	27.71
SEm±	0.14	0.34	0.29	0.28
CD (P=0.05)	0.44	1.06	0.90	0.87
(Factor I × M)	NS	NS	NS	NS

Number of silique per plant: The number of silique per plant at harvest was significantly influenced by both irrigation and nitrogen levels. Irrigation at 0.09 IW/CPE with mulch recorded a significantly higher number of silique (79.90) compared to 0.06 IW/CPE without mulch (78.89). Among nitrogen treatments, the highest number of silique (80.92) was observed at 125% RDN, which was significantly superior to lower nitrogen levels Table 6. The interaction effect between irrigation and nitrogen was also found to be significant, Patel *et al.* (2015) [6].

Table 6: Effect on irrigation and nitrogen with and without mulch on Number of silique per plant at harvest.

Treatments	Number of silique per plant
	At harvest
Irrigation 0.06 without Mulch	78.89
Irrigation 0.09 with Mulch	79.90
SEm±	0.01
CD (P=0.05)	0.05
Nitrogen Level (RDN)	
(RDN50 %)	77.87
(RDN 75 %)	78.89
(RDN 100 %)	79.90
(RDN125 %)	80.92
SEm±	0.02
CD (P=0.05)	0.07
(Factor I × M)	0.10

Number of seeds per silique: The number of seeds per silique at harvest was significantly influenced by both irrigation and nitrogen levels. Irrigation at 0.09 IW/CPE with mulch recorded a significantly higher seed count (19.82) compared to 0.06 IW/CPE without mulch (18.75). Among nitrogen treatments, the maximum number of seeds per silique (20.87) was obtained with 125% RDN, which was significantly higher than the lower nitrogen levels Table 7. The interaction between irrigation and nitrogen was also found to be significant. Although the difference was not statistically significant, the trend suggests that improved soil moisture and temperature regulation under mulch may enhance flowering and pod setting, consistent with the findings of Patel *et al.* (2017) [8], who reported improved reproductive traits under mulched conditions.

Table 7: Effect on irrigation and nitrogen with and without mulch on Number of seeds per silique at harvest.

Treatments	Number of seeds per silique
	At harvest
Irrigation 0.06 without Mulch	18.75
Irrigation 0.09 with Mulch	19.82
SEm±	0.008
CD (P=0.05)	0.02
Nitrogen Level (RDN)	
(RDN50 %)	17.73
(RDN 75 %)	18.75
(RDN 100 %)	19.80
(RDN125 %)	20.87
SEm±	0.012
CD (P=0.05)	0.03
(Factor I × M)	0.05

Test weight: Test weight at harvest was significantly affected by both irrigation and nitrogen levels. The highest test weight (4.69 g) was recorded under 0.09 IW/CPE with mulch, which was significantly higher than 0.06 IW/CPE without mulch (4.40 g). Among nitrogen treatments, 125% RDN produced the maximum test weight (5.32 g), significantly superior to all other nitrogen levels. The interaction effect between irrigation and nitrogen was also found to be significant Table 8. The increase may be attributed to improved soil moisture and nutrient availability under mulched conditions, which enhances fertilization and seed setting, as supported by Meena *et al.* (2023) [17], who reported similar improvements in seed yield attributes under mulching in oilseed crops.

Table 8: Effect on irrigation and nitrogen with and without mulch on test weight.

Treatments	Test weight
	At harvest
Irrigation 0.06 without Mulch	4.40
Irrigation 0.09 with Mulch	4.69
SEm±	0.01
CD (P=0.05)	0.03
Nitrogen Level (RDN)	
(RDN50 %)	4.14
(RDN 75 %)	4.31
(RDN 100 %)	4.41
(RDN125 %)	5.32
SEm±	0.01
CD (P=0.05)	0.05
(Factor I × M)	0.07

Seed yield, straw yield and harvest index: The data on seed yield, straw yield, and harvest index. Irrigation at 0.09 IW/CPE with mulch recorded higher seed yield (1822.56 kg/ha), straw yield (3515.62 kg/ha), and harvest index (0.34) compared to 0.06 IW/CPE without mulch. Among nitrogen treatments, the highest seed yield (1926.00 kg/ha), straw yield (3639.36 kg/ha), and harvest index (0.34) were observed with 125% RDN, significantly superior to lower nitrogen levels Table 8. The interaction effect between irrigation and nitrogen was also significant for all parameters Raj *et al.* (2021) [13].

Table 9: Effect on irrigation and nitrogen with and without mulch on Seed yield, straw yield at harvest.

Treatments	At harvest		
	Seed yield kg/ha	straw yield kg/ha	Harvest index (%)
Irrigation 0.06 without Mulch	1716.95	3406.23	0.33
Irrigation 0.09 with Mulch	1822.56	3515.62	0.34
SEm±	0.37	0.47	0.001
CD (P=0.05)	1.14	1.44	0.002
Nitrogen Level (RDN)			
(RDN50 %)	1614.04	3313.05	0.32
(RDN 75 %)	1718.02	3390.75	0.33
(RDN 100 %)	1820.66	3500.54	0.34
(RDN125 %)	1926.00	3639.36	0.34
SEm±	0.52	0.66	0.001
CD (P=0.05)	1.61	2.04	0.003
(Factor I × M)	2.28	2.89	0.004

Biological yield: The data on biological yield at harvest was significantly influenced by both irrigation and nitrogen levels. Higher biological yield (5338.00 kg/ha) was recorded under 0.09 IW/CPE with mulch compared to 0.06 IW/CPE without mulch (5123.25 kg/ha). Among nitrogen treatments, the maximum biological yield (5665.50 kg/ha) was observed with 125% RDN, which was significantly superior to other nitrogen levels. The interaction between irrigation and nitrogen was also significant. The improvement in biological yield under mulched conditions may be due to better soil moisture conservation, enhanced root growth, and improved overall plant vigour. These results are consistent with the findings of Raj *et al.* (2019) [12], who reported increased biomass production in oilseed crops under mulched and optimally irrigated conditions.

Oil content in seeds: The data on protein and oil content in seeds were significantly influenced by both irrigation and nitrogen levels. Irrigation at 0.09 IW/CPE with mulch resulted in significantly higher protein content (22.88%) and oil content (40.13%) compared to 0.06 IW/CPE without mulch. Among nitrogen levels, the highest protein (23.87%) and oil content (40.92%) were recorded under 125% RDN, which was significantly superior to the lower nitrogen levels Table 10. The interaction between irrigation and nitrogen was also found to be significant for both parameters. These findings are in agreement with Meena *et al.* (2023) [17], who reported enhanced seed composition in oilseed crops under mulched irrigation.

Table 10: Effect on irrigation and nitrogen with and without mulch on biological yield at harvest.

Treatments	Biological yield
	At harvest
Irrigation 0.06 without Mulch	5123.25
Irrigation 0.09 with Mulch	5338.00
SEm±	0.53
CD (P=0.05)	1.62
Nitrogen Level (RDN)	
(RDN50 %)	4927.33
(RDN 75 %)	5108.66
(RDN 100 %)	5321.00
(RDN125 %)	5565.50
SEm±	0.75
CD (P=0.05)	2.30
(Factor I × M)	3.25

Soil properties
Soil chemical
pH, and electrical conductivity: The soil pH and electrical conductivity after sowing were significantly affected by both irrigation and nitrogen levels. Higher pH (7.39) and electrical conductivity (0.22 dS/m) were observed under 0.09 IW/CPE with mulch compared to 0.06 IW/CPE without mulch. Among nitrogen treatments, the highest pH (7.46) and electrical conductivity (0.24 dS/m) were recorded under 125% RDN, which were significantly superior to other levels. However, the interaction effect between irrigation and nitrogen levels was found to be non-significant for both parameters Table 11. This slight increase in soil pH and EC could be due to enhanced mineralization and solute movement under better moisture conditions, as also observed by Rajput *et al*. (2016) [14], who reported improved nutrient solubility under mulched irrigation in oilseed crops.

Table 11: Effect on irrigation and nitrogen with and without mulch on Protein content in seeds and oil content in seeds at harvest.

Treatments	At harvest	
	Protein content in seeds	**Oil content in seeds**
Irrigation 0.06 without Mulch	21.83	38.98
Irrigation 0.09 with Mulch	22.88	40.13
SEm±	0.002	0.06
CD (P=0.05)	0.007	0.20
Nitrogen Level (RDN)		
(RDN50 %)	20.84	37.98
(RDN 75 %)	21.85	39.24
(RDN 100 %)	22.86	40.07
(RDN125 %)	23.87	40.92
SEm±	0.003	0.09
CD (P=0.05)	0.010	0.29
(Factor I × M)	0.015	0.41

Organic carbon: The data on organic carbon content in soil was significantly influenced by both irrigation and nitrogen levels. Irrigation at 0.09 IW/CPE with mulch recorded significantly higher organic carbon (0.75%) compared to 0.06 IW/CPE without mulch (0.59%) Table 12. Among nitrogen levels, the highest organic carbon (0.79%) was observed with 125% RDN, which was significantly superior to the other treatments. The interaction between irrigation and nitrogen was found to be non-significant. The increased organic carbon under mulched irrigation is likely due to improved moisture retention, microbial activity, and reduced organic matter decomposition losses, aligning with the findings of Patel *et al*. (2020) [20], Yadav *et al*. (2021) [13], who noted mulch-induced enhancement in SOC due to moderated soil temperature and reduced erosion.

Table 12: Effect on irrigation and nitrogen with and without mulch on pH, and electrical conductivity.

Treatments	After sowing	
	pH,	**EC (DS m-1)**
Irrigation 0.06 without Mulch	7.23	0.19
Irrigation 0.09 with Mulch	7.39	0.22
SEm±	0.009	0.005
CD (P=0.05)	0.028	0.015
Nitrogen Level (RDN)		
(RDN50 %)	7.18	0.17
(RDN 75 %)	7.27	0.20
(RDN 100 %)	7.35	0.21
(RDN125 %)	7.46	0.24
SEm±	0.013	0.007
CD (P=0.05)	0.040	0.021
(Factor I × M)	NS	NS

Available N P and K: The data on available nitrogen, phosphorus, and potassium in soil were significantly affected by irrigation and nitrogen levels. The highest values for available N (188.15 kg/ha), P (22.38 kg/ha), and K (421.57 kg/ha) were observed under 0.09 IW/CPE with mulch, significantly superior to 0.06 IW/CPE without mulch. Among nitrogen levels, 125% RDN recorded the maximum available N (190.78 kg/ha), P (24.37 kg/ha), and K (403.73 kg/ha), significantly higher than the lower nitrogen levels Table 13 & 14. However, the interaction between irrigation and nitrogen was non-significant for all parameters. The improvement under mulch is likely due to better nutrient conservation and reduced leaching losses, as mulch minimizes evaporation and maintains favourable microbial activity Patel *et al.*, (2019) [11].

Table 13: Effect on irrigation and nitrogen with and without mulch on Organic carbon.

Treatments	SOC
Irrigation 0.06 without Mulch	0.59
Irrigation 0.09 with Mulch	0.75
SEm±	0.012
CD (P=0.05)	0.038
Nitrogen Level (RDN)	
(RDN50 %)	0.59
(RDN 75 %)	0.62
(RDN 100 %)	0.68
(RDN125 %)	0.79
SEm±	0.018
CD (P=0.05)	0.054
(Factor I × M)	NS

Table 14: Effect on irrigation and nitrogen with and without mulch on Available N P and K.

Treatments	Available		
	N	P	K
Irrigation 0.06 without Mulch	178.99	18.65	363.12
Irrigation 0.09 with Mulch	188.15	22.38	421.57
SEm±	0.60	0.40	3.17
CD (P=0.05)	1.84	1.25	9.71
Nitrogen Level (RDN)			
(RDN50 %)	178.52	16.90	381.27
(RDN 75 %)	181.57	19.82	388.15
(RDN 100 %)	183.42	20.97	396.22
(RDN125 %)	190.78	24.37	403.73
SEm±	0.84	0.57	4.48
CD (P=0.05)	2.60	1.77	13.73
(Factor I × M)	NS	NS	NS

Conclusion

The study found that irrigating mustard at critical growth stages, especially during branching and flowering, significantly improved both growth and yield. Two irrigations proved more effective than one or no irrigation in enhancing water use efficiency and seed yield. Maintaining adequate moisture during the reproductive phase, particularly during flowering, was essential to prevent flower drop and ensure proper seed setting. Applying up to 120 kg/ha of nitrogen boosted plant growth and yield, with the best results achieved when combined with optimal irrigation and mulch. Mulch played a key role in conserving moisture, reducing evaporation, and promoting microbial activity, all of which contributed to higher yields and healthier soil. The combination of two irrigations, 120 kg N/ha, and mulch was the most effective for improving growth, yield, and economic returns. This treatment also optimized water use efficiency, while excess irrigation decreased efficiency and caused nutrient leaching.

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