Plant Archives Vol. 26, No. 2, 2026 pp. 2925-2934 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.no.2.402

GROWTH, PRODUCTIVITY AND ECONOMIC PERFORMANCE OF *RABI* MUSTARD (*Brassica juncea* L.) UNDER CONVENTIONAL AND NANO-UREA-BASED NITROGEN MANAGEMENT

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(Date of Receiving-03-08-2026; Date of Revision-10-10-2026; Date of Acceptance-15-10-2026)

ABSTRACT

Nitrogen management is an important determinant of growth, yield formation and economic returns in mustard, while efficient nitrogen application is essential for improving crop productivity. A field experiment was conducted during *rabi* 2021–22 at the Agricultural Research Institute, PJTSAU, Rajendranagar, Hyderabad, Telangana, to evaluate the effects of conventional soil-applied nitrogen and foliar nano-urea application on growth attributes, leaf area index (LAI), dry matter accumulation, yield attributes, seed and stalk yield, harvest index and economics of mustard (*Brassica juncea* L.). The experiment was conducted in a randomized block design with eight treatments and three replications. Treatments included no nitrogen, conventional nitrogen application and combinations of basal nitrogen with foliar nano-urea at different concentrations applied at the rosette and flowering stages. Nitrogen management significantly influenced growth and yield-related parameters. The treatment comprising ½ RDN at sowing + foliar nano-urea @ 4 mL L^{-1} at rosette and flowering (T_8) recorded the highest plant height, LAI and dry matter accumulation at harvest (156.0 cm, 0.98 and 29.2 g $plant^{-1}$, respectively). It also recorded the highest number of branches (10.0 $plant^{-1}$), siliquae (1593 m^{-2}) and grain weight (4.37 g $plant^{-1}$). T_8 produced the highest seed yield (1126 kg ha^{-1}) and stalk yield (1904 kg ha^{-1}) and recorded the highest harvest index (37.2%). Economic analysis showed that T_8 recorded the highest gross returns (` 58,772 $ha^{-1}$), net returns (` 31,994 ha^{-1}) and benefit:cost ratio (2.19). Thus, under the conditions of the present study, integration of basal conventional nitrogen with foliar nano-urea application at the rosette and flowering stages improved growth, yield attributes, seed and stalk productivity, harvest index and economic returns of *rabi* mustard.

Key words : Mustard (*Brassica juncea*), Nano-fertilizers, Nano-urea, Nano technology, Split application, Nitrogen management, Oilseeds.

Introduction

Oilseed crops play an important role in Indian agriculture, contributing substantially to agricultural output and edible-oil availability. Despite being a major oilseed-producing country, India continues to depend on imports to meet domestic edible-oil demand, highlighting the need to improve oilseed productivity through efficient agronomic practices and improved nutrient management. India's oilseed production reached 429.89 lakh tonnes (42.99 million tonnes) during the 2024–25 crop year, with the area under oilseed cultivation expanding to 304.40 lakh hectares (Department of Agriculture & Farmers Welfare, 2026). Among the major oilseed crops, rapeseed and mustard production was 126.67 lakh tonnes during 2024–25 (PIB, 2025). Mustard (*Brassica juncea* L.) is an important edible oilseed crop in India and contributes

nearly one-third of the country's oil production. The crop is traditionally concentrated in northern and north-western India, while its cultivation in Telangana is comparatively limited. However, favourable climatic and edaphic conditions, increasing irrigation potential and opportunities in rice-fallow systems indicate scope for expanding *rabi* mustard cultivation in the state.

Nitrogen (N) is a key nutrient governing vegetative growth and crop productivity through its role in chlorophyll, proteins and enzymes. However, inefficient management of conventional N fertilizers can result in substantial N losses and reduced nitrogen-use efficiency (NUE). Surface-applied urea is particularly susceptible to ammonia volatilization, while difficulties associated with uniform top-dressing under field conditions can further reduce fertilizer-use efficiency. Conventional fertilizers and their application practices often result in relatively low nitrogen (N) use efficiency, typically ranging from 30–45%, leading to considerable N losses and highlighting the need for more efficient and sustainable nutrient-management strategies (Reddy *et al*., 2025). In recent years, nanotechnology has gained attention as a potential approach for improving nitrogen-use efficiency (NUE) and promoting sustainable crop production. Nano-fertilizers, typically characterized by particle sizes in the nanometre range, offer a high surface area and enhanced reactivity, which may facilitate more efficient nutrient delivery and better synchronization of nutrient availability with crop demand. These characteristics can potentially enhance nutrient uptake, while reducing nutrient losses (Singh *et al.*, 2024). Nano-based products, including nano urea, nano DAP and nano zinc, are increasingly being explored and promoted as alternatives or supplements to conventional fertilizers because of their potential for improving nutrient-use efficiency and reducing environmental losses (Kekeli *et al.*, 2025).

Nanotechnology-based fertilizers have emerged as an alternative approach for improving nutrient-use efficiency. Nano-fertilizers can be applied through soil or foliar routes and have been proposed to improve nutrient availability and delivery to plants because of their distinctive physicochemical properties. Their potential to improve nutrient-use efficiency and partially reduce dependence on conventional soil-applied fertilizers has also been reported (Seleiman *et al*., 2021). Increased nutrient availability and greater surface area associated with nano-fertilizers may influence nutrient assimilation and crop growth. Foliar nano-urea application at critical growth stages may improve N-use efficiency and crop productivity. However, its effectiveness under Telangana conditions depends on the nano-N concentration and integration with conventional N. Therefore, the present study evaluated the effects of conventional soil-applied N and foliar nano-urea on growth, yield and economic performance of *rabi* mustard.

Materials and Methods

Experimental site and season

A field experiment was conducted during *rabi* 2021–22 at the Agricultural Research Institute, Professor Jayashankar Telangana State Agricultural University (PJTSAU), Rajendranagar, Hyderabad, Telangana, India (17°19′ 44″ N, 78°23′ 55″ E; 523 m above mean sea level). The experimental site falls under the Southern Telangana agro-climatic zone and the semi-arid tropical region. The soil of the experimental field was clay in texture, with pH 7.86, electrical conductivity 0.32 dS m^{-1} and organic carbon 0.34%. Initial soil available N, P and K were 31.8 mg kg^{-1} NH_4-N, 16.2 mg kg^{-1} NO_3-N, 29.31 kg ha^{-1} and 386 kg ha^{-1}, respectively.

Experimental design and treatments

The experiment was laid out in a randomized block design (RBD) with eight nitrogen-management treatments and three replications, using mustard hybrid NRCHB-101. The crop was sown on 15 November 2021 at a spacing of 45 × 20 cm. The gross and net plot sizes were 8.0 × 5.0 m and 5.4 × 3.8 m, respectively.

The treatments were:

Treatment	Nitrogen management
T_1	No nitrogen
T_2	½ RDN at sowing + ½ RDN at flowering
T_3	½ RDN at sowing + nano-N @ 4 mL L^{-1} at flowering
T_4	½ RDN at sowing + nano-N @ 2 mL L^{-1} at rosette and flowering
T_5	½ RDN at sowing + nano-N @ 2.5 mL L^{-1} at rosette and flowering
T_6	½ RDN at sowing + nano-N @ 3 mL L^{-1} at rosette and flowering
T_7	½ RDN at sowing + nano-N @ 3.5 mL L^{-1} at rosette and flowering
T_8	½ RDN at sowing + nano-N @ 4 mL L^{-1} at rosette and flowering

The recommended fertilizer dose for mustard was 60:40:40 kg N:P_2O_5 :K_2O ha^{-1}. Phosphorus and potassium were applied basally at sowing, while nitrogen was managed according to the respective treatments.

Crop management and foliar nano-urea application

Nitrogen was supplied through urea, while single super

phosphate and muriate of potash were used as sources of P and K, respectively. Half of the recommended N was applied basally and the remaining N was applied according to the treatment schedule. IFFCO Nano Urea Liquid was used as the foliar nano-N source. A spray volume of 312 L ha^{-1} per application was used, and foliar application was carried out using a hand-operated pneumatic sprayer. The crop was managed using recommended agronomic practices. Gap filling and thinning were performed to maintain the desired plant population, while irrigation, weed management and plant protection measures were applied uniformly across treatments. Growth and yield-related observations were recorded from representative plants selected from each plot.

Growth parameters : Plant height, leaf area index (LAI) and dry matter accumulation were recorded at the rosette, flowering and harvest stages. Plant height was measured from the base to the growing point. Dry matter was determined after oven-drying plant samples to constant weight and expressed as g $plant^{-1}$; harvest dry matter was also expressed as kg ha^{-1}. LAI was determined using a leaf area meter and calculated as the ratio of total leaf area to land area occupied by the plants.

Yield attributes : At harvest, test weight, number of branches $plant^{-1}$, grain weight $plant^{-1}$ and number of siliquae m{ ² were recorded. Test weight was determined from 1000 seeds, while siliquae were counted using a 1 m^2 quadrat.

Yield and harvest index

The crop was harvested manually when the siliquae turned yellow and the seeds attained their characteristic dark-brown colour. After drying, threshing and cleaning, seed yield was recorded from the net plot and expressed as kg ha^{-1}. Stalk yield was determined from the dried stalks/haulms obtained from the net plot and expressed as kg ha^{-1}.



Plate 1 : Tagging of Representative plants and intercultural operations in Mustard.

Economic analysis

The cost of cultivation, gross returns, net returns and benefit:cost ratio (B:C) were calculated for each treatment. Cost of cultivation was estimated using prevailing input prices. Gross returns were calculated from the income obtained from seed yield, while net returns were calculated as the difference between gross returns and cost of cultivation. The B:C ratio was calculated as the ratio of gross returns to cost of cultivation.

Statistical analysis

The experimental data were subjected to analysis of variance (ANOVA) for randomized block design following Gomez and Gomez (1984). Treatment means were compared using Duncan's multiple range test (DMRT) at $p \leq 0.05$. Correlation and regression analyses were performed using Microsoft Excel 2013.

Results and Discussion

Plant height (cm)

Plant height increased progressively with crop growth and was significantly influenced by nitrogen management at flowering and harvest. At the rosette stage, plant height did not differ significantly among the nitrogen-supplied treatments (T_2–T_8), as all received an equal basal dose of soil-applied urea before foliar nano-urea application. The no-N treatment (T_1) recorded the shortest plants. At flowering, T_8 recorded the tallest plants (140.2 cm), which was statistically comparable with T_7 (135.4 cm), whereas T_1 recorded the lowest height (80.0 cm). At harvest, T_8 again recorded the maximum plant height (156.0 cm), comparable with T_7 (148.1 cm) and T_2 (140.0 cm), while T_1 remained the shortest (90.4 cm). The greater plant height with foliar nano-urea may be associated with improved N availability during active crop growth. Marimuthu and Surendran (2015), Ahmed *et al.* (2019) reported that plant height of their test crops (black gram and maize, respectively) was directly improved by the application of nano fertilizer.

Leaf area index

Leaf area index (LAI) was significantly influenced by nitrogen management. At the rosette stage, all nitrogen-supplied treatments recorded statistically similar LAI because an equal basal N dose was applied and nano-urea spraying had not yet commenced. The control (T_1) recorded the lowest LAI (0.44). At flowering, T_8 (½ RDN at sowing + nano-N @ 4 mL L^{-1} at rosette and flowering) recorded the highest LAI (2.76), followed by T_7 (2.56), whereas T_1 recorded the lowest value (0.81). At harvest, T_8 maintained the highest LAI (0.98), which was comparable with T_2 (0.96). The greater LAI under higher

Table 1 : Influence of foliar application of nano urea on plant height of mustard.

Treatments	Plant height (cm)		
	Rosette (30 DAS)	Flowering (60 DAS)	At harvest
T_1 : No Nitrogen application	21.1[b]	80.0[c]	90.4[c]
T_2: ½ RDN at sowing + ½ RDN at flowering	46.0[a]	105.1[b]	140.0[a]
T_3: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at flowering	51.3[a]	106.8[b]	115.1[b]
T_4: ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} at rosette stageand flowering	48.0[a]	109.2[b]	121.1[b]
T_5: ½ RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1} at rosettestage and flowering	47.2[a]	113.0[b]	127.2[b]
T_6: ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1} at rosette stageand flowering	50.1[a]	118.0[b]	133.5[b]
T_7: ½ RDN at sowing + foliar spray of nano-N @ 3.5 ml L^{-1} at rosettestage and flowering	52.0[a]	135.4[a]	148.1[a]
T_8: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at rosette stageand flowering	49.0[a]	140.2[a]	156.0[a]
SEm ±	2.21	5.34	6.51
CD (p=0.05)	6.72	16.2	19.75
CV%	8.4	8.2	8.8

*Nano urea spray was done after 30 DAS.

nano-N concentrations may have resulted from improved nutrient acquisition and enhanced canopy development, thereby increasing the photosynthetic surface. The decline in LAI towards maturity was associated with progressive leaf senescence. Similar enhancement in leaf development following foliar nano-nitrogen application was reported by Abdel-Aziz *et al.* (2018).

Dry matter accumulation at critical growth stages (g plant^{-1}) and harvest (kg ha^{-1})

Dry matter accumulation increased progressively with crop growth and was significantly influenced by nitrogen management. At the rosette stage, N-supplied treatments were statistically comparable, while the control (T_1) recorded the lowest dry matter (4.1 g plant^{-1}). At flowering, T_8 recorded the highest dry matter (18.6 g plant^{-1}), comparable with T_7 (17.8 g plant^{-1}). At harvest, T_8 maintained the highest value (29.2 g plant^{-1}), statistically comparable with T_7 (27.7 g plant^{-1}) and T_2 (26.9 g plant^{-1}). On a hectare basis, T_8 recorded the highest dry matter production (3260 kg ha^{-1}), followed by T_7 (3080 kg ha^{-1}) and T_2 (2990 kg ha^{-1}), whereas T_1 recorded the lowest (1485 kg ha^{-1}). The higher biomass under T_8 may be associated with improved plant height and leaf area, providing greater photosynthetic surface for biomass accumulation. Similar improvements in dry matter production with nano-fertilizer application were reported by Qureshi *et al.* (2018).

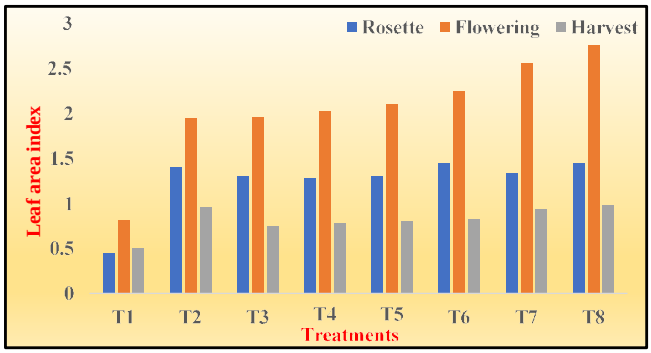


Fig. 1 : Influence of foliar application of nano urea on leaf area index of mustard.

Yield attributes

Test weight (g)

Test weight was not significantly influenced by nitrogen management treatments. The treatment means ranged from 3.45 g in T_1 to 3.91 g in T_8, with an overall mean of 3.73 g. The non-significant variation in test weight suggests that the different nitrogen management practices had limited influence on this yield attribute under the conditions of the present study.

Number of branches plant^{-1} at harvest

Nitrogen management significantly influenced the number of branches plant^{-1} at harvest. T_8 recorded the

Table 2 : Influence of foliar application of nano urea on leaf area index (LAI) of mustard.

Treatments	LAI		
	Rosette (30 DAS)	Flowering (60 DAS)	At harvest
T_1 : No Nitrogen application	0.44[b]	0.81[c]	0.50[c]
T_2: ½ RDN at sowing + ½ RDN at flowering	1.40[a]	1.95[b]	0.96[a]
T_3: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at flowering	1.30[a]	1.96[b]	0.75[b]
T_4: ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} at rosette stageand flowering	1.28[a]	2.03[b]	0.78[b]
T_5: ½ RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1} at rosettestage and flowering	1.30[a]	2.10[b]	0.80[b]
T_6: ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1} at rosette stageand flowering	1.45[a]	2.25[b]	0.81[b]
T_7: ½ RDN at sowing + foliar spray of nano-N @ 3.5 ml L^{-1} at rosettestage and flowering	1.34[a]	2.56[a]	0.94[a]
T_8: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at rosette stageand flowering	1.45[a]	2.76[a]	0.98[a]
SEm ±	0.06	0.10	0.04
CD (p=0.05)	0.19	0.32	0.12
CV%	8.88	8.83	8.62

*Nano urea spray was done after 30 DAS.

highest number of branches (10.0 plant^{-1}), which was statistically comparable with T_7 (9.8), T_2 (9.5) and T_6 (8.7), whereas T_1 recorded the lowest value (5.0 plant^{-1}). The greater branching observed with higher rates of foliar nano-N may be associated with improved nitrogen availability during active vegetative growth, which can promote plant growth and development. The present findings are supported by Midde *et al*. (2021), who reported improved tillering in rice following nano-fertilizer application and attributed the response to the greater specific surface area and enhanced interaction of nano-sized fertilizer particles with the plant system.

Grain weight plant^{-1}

Grain weight plant^{-1} was significantly influenced by nitrogen management. T_8 recorded the highest grain weight (4.37 g plant^{-1}), which was statistically comparable with T_7 (4.15 g plant^{-1}) and T_2 (4.07 g plant^{-1}), while T_1 recorded the lowest value (1.45 g plant^{-1}). The higher grain weight under T_8 may be associated with improved crop growth and reproductive development resulting from adequate nitrogen availability during critical growth stages. Sahu *et al.* (2022) reported enhanced grain production with foliar nano-urea application and associated the response with improved nitrogen availability and photosynthetic activity. Similar improvements in yield-related traits following nano-fertilizer application were also reported by Gewaily *et al.* (2019).

Number of siliquae m^{-2}

Nitrogen management significantly affected the number of siliquae m^{-2}. T_8 recorded the highest number of siliquae (1593 m^{-2}), which was statistically comparable with T_7 (1511 m^{-2}) and T_2 (1433 m^{-2}), whereas T_1 recorded the lowest value (953 m^{-2}). The greater number of siliquae under T_7 and T_8 may be attributed to improved nitrogen availability during the reproductive phase, which supported branching and reproductive development. Comparable findings were also reported by Jassim *et al.* (2019).

Seed yield (kg ha^{-1})

Seed yield was significantly influenced by nitrogen management. T_8 recorded the highest seed yield (1126 kg ha^{-1}), statistically comparable with T_7 (985 kg ha^{-1}) and T_2 (975 kg ha^{-1}). T_6, T_4, T_5 and T_3 recorded 885, 694, 704 and 529 kg ha^{-1}, respectively, while T_1 recorded the lowest yield (367 kg ha^{-1}). The higher yield with two foliar nano-N applications at rosette and flowering indicates the importance of application timing and concentration. The superior performance of T_7 and T_8 was associated with higher siliquae number and grain weight; T_8 recorded 1593 siliquae m^{-2} and 4.37 g grain weight plant^{-1}, compared with 953 siliquae m^{-2} and 1.45

Table 3 : Influence of foliar application of nano urea on dry matter accumulation at critical growth stages and harvest on mustard.

Treatments	Dry matter (g plant^{-1})		
	Rosette (30 DAS)	Flowering (60 DAS)	At harvest
T_1 : No Nitrogen application	4.1^{b}	6.4^{c}	13.4^{e}
T_2: ½ RDN at sowing + ½ RDN at flowering	12.3^{a}	13.7^{b}	26.9^{ab}
T_3: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at flowering	12.2^{a}	13.8^{b}	16.9^{d}
T_4: ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} at rosette stage and flowering	11.7^{a}	14.0^{b}	20.5^{c}
T_5: 1/2RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1} at rosette stage and flowering	11.6^{a}	15.0^{b}	20.8^{c}
T_6: ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1}at rosette stage and flowering	12.6^{a}	15.8^{b}	24.3^{b}
T_7: ½ RDN at sowing+ foliar spray of nano-N @ 3.5 ml L^{-1} at rosette stage and flowering	11.9^{a}	17.8^{a}	27.7^{ab}
T_8: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at rosette stage and flowering	12.8^{a}	18.6^{a}	29.2^{a}
SEm ±	0.6	0.7	1.2
CD (p=0.05)	1.8	2.2	3.8
CV%	9.4	8.6	9.5

*Nano urea spray was done after 30 DAS.

Table 4 : Influence of foliar application of nano urea on dry matter accumulation at harvest of mustard.

Treatments	Dry matter (kg ha^{-1})
T_1 : No Nitrogen application	1485^{e}
T_2: ½ RDN at sowing + 1/2 RDN at flowering	2990^{ab}
T_3: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at flowering	1880^{d}
T_4: ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} at rosette stage and flowering	2275^{c}
T_5: ½ RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1} at rosette stage and flowering	2310^{c}
T_6: ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1} at rosette stage and flowering	2705^{b}
T_7: ½ RDN at sowing + foliar spray of nano-N @ 3.5 ml L^{-1} at rosette stage and flowering	3080^{ab}
T_8: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at rosette stage and flowering	3260^{a}
SEm ±	126.8
CD (p=0.05)	384.5
CV%	8.8

g plant^{-1} in T_1. Similar improvements in crop productivity following nano-fertilizer application were reported by Drostkar *et al.* (2016), Tarafdar *et al.* (2012).

Stalk yield (kg ha^{-1})

Stalk yield was significantly influenced by nitrogen management. T_8 recorded the highest stalk yield (1904 kg ha^{-1}), which was statistically comparable with T_7 (1872 kg ha^{-1}) and T_2 (1832 kg ha^{-1}). The lowest stalk yield was recorded in the control (T_1; 865 kg ha^{-1}). In contrast, T_3, which received a single foliar application of nano-N @ 4 mL L^{-1} at flowering, produced only 1121 kg ha^{-1}. Thus, application of nano-N at both rosette and flowering stages resulted in greater stalk production than a single application at flowering. The higher stalk yield under T_7 and T_8 was associated with greater plant height, leaf area and dry matter accumulation observed under these treatments. The greater vegetative growth under repeated foliar nano-N application may have contributed to increased biomass production and, consequently, stalk yield. Previous studies have also reported positive responses of crop biomass and yield to nano-fertilizer application. Mehta and Bharat (2019) reported improved

Table 5 : Influence of foliar application of nano urea on yield attributes of mustard.

Treatments	Test weight (g)	No. of branches at harvest	Grain weight per plant^{-1}	No. of siliqua m^{-2}
T_1 : No Nitrogen application	3.45	5.0^{c}	1.45^{e}	953^{c}
T_2 : ½ RDN at sowing + 1/2 RDN at flowering	3.82	9.5^{a}	4.07^{ab}	1433^{a}
T_3 : ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} atflowering	3.68	6.8^{b}	2.25^{d}	1155^{b}
T_4 : ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} atrosette stage and flowering	3.65	7.0^{b}	2.90^{c}	1210^{b}
T_5 : ½ RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1} atrosette stage and flowering	3.69	7.2^{b}	2.90^{c}	1244^{b}
T_5 : ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1} atrosette stage and flowering	3.75	8.7^{a}	3.60^{b}	1278^{b}
T_7 : ½ RDN at sowing + foliar spray of nano-N @ 3.5 ml L^{-1} atrosette stage and flowering	3.86	9.8^{a}	4.15^{ab}	1511^{a}
T_8 : ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} atrosette stage and flowering	3.91	10.0^{a}	4.37^{a}	1593^{a}
SEm±	0.19	0.4	0.22	68.3
CD (p=0.05)	NS	1.4	0.67	207.1
CV%	8.66	9.6	11.96	9.1

stalk yield in wheat under nano-fertilizer-based nutrient management, while Dhaliwal *et al*. (2021) reported similar beneficial responses in mustard.

Harvest index (%)

Harvest index was significantly affected by nitrogen management when the nitrogen-supplied treatments were compared with the control, whereas the differences among the fertilized treatments were not significant. The highest harvest index was recorded in T_8 (37.2%), while the lowest value was observed in T_1 (29.8%). T_2, T_6, T_7 and the other nitrogen-supplied treatments recorded statistically comparable harvest index values. The relatively higher harvest index in T_8 corresponded with its greater seed yield, although the differences among nitrogen-supplied treatments were statistically non-significant.

Interpretation

- **Rosette(30DAS)**

  Dry matter showed a positive linear relationship with seed yield, with R^2 = 0.5068. Thus, approximately 50.68% of the variation in seed yield was associated with variation in dry matter at the rosette stage.

- **Flowering (60DAS)**

  The relationship became stronger, with R^2 = 0.7113, indicating that approximately 71.13% of the variation in seed yield was associated with dry matter accumulation at flowering.

- **Harvest**

  The strongest relationship was observed, with R^2 = 0.9933. This indicates that approximately 99.33% of the variation in seed yield was associated with dry matter accumulation at harvest in the observed treatments.

Economics

Economic analysis

The economic performance of the nitrogen management treatments was evaluated based on treatment-wise cost of cultivation, gross returns, net returns and benefit–cost ratio. The variation in economic returns was primarily associated with differences in seed and stalk yields and the corresponding costs of nitrogen management.

Cost of cultivation

Cost of cultivation varied among treatments according to the nitrogen source and application strategy. T_1 recorded the lowest cost of cultivation (` 25,188 ha$^{-1}$), owing to the absence of external nitrogen application. The cost increased with the inclusion of nano-N and additional nitrogen inputs. $T_8$ recorded a cost of cultivation of ` 26,778 ha^{-1}, compared with ` 25,968 ha^{-1} under the conventional split-N treatment (T_2). The additional

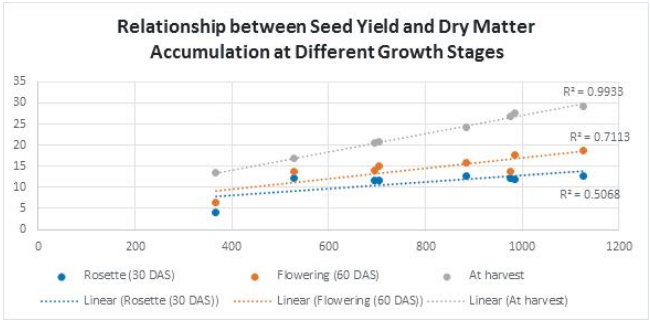


Fig. 2 : Relationship between Seed yield and Dry matter accumulation at different Growth stages.

31,994 ha^{-1}), followed by T_2 (` 25,102 ha$^{-1}$) and $T_7$ (` 24,987 ha^{-1}). T_6 recorded ` 19,872 ha$^{-1}$, whereas $T_1$ resulted in a negative net return of ` 5,806 ha^{-1}. The single foliar application treatment T_3 generated only ` 1,658 ha$^{-1}$, while the two-spray treatments $T_4$ and $T_5$ resulted in ` 10,250 and ` 10,612 ha^{-1}, respectively. The higher net returns under T8 were associated with its greater seed and stalk yields, which offset the additional cost of nano-N application. Kumar *et al.* (2021) also reported improved economic returns in mustard under reduced conventional N combined with foliar nano-

Table 6 : Influence of foliar application of nano urea on yield of mustard.

Treatments	Seed yield (kg ha^{-1})	Stalk yield (kg ha^{-1})	Harvest index (%)
T_1 : No Nitrogen application	367^{e}	865^{e}	29.8^{b}
T_2: ½ RDN at sowing + 1/2 RDN at flowering	975^{ab}	1832^{ab}	34.7^{a}
T_3: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} atflowering	529^{d}	1121^{d}	32.1^{a}
T_4: ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} at rosettestage and flowering	694^{c}	1381^{c}	33.1^{a}
T_5: ½ RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1} at rosettestage and flowering	704^{c}	1405^{c}	33.4^{a}
T_6: ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1} at rosettestage and flowering	885^{b}	1658^{b}	34.8^{a}
T_7: ½ RDN at sowing + foliar spray of nano-N @ 3.5 ml L^{-1} at rosettestage and flowering	985^{ab}	1872^{ab}	34.5^{a}
T_8: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} at rosettestage and flowering	1126^{a}	1904^{a}	37.2^{a}
SEm±	52	74	1.7
CD (p=0.05)	157	224	5.2
CV%	11	8	8.8

nitrogen-management expenditure in T_8 was associated with the higher seed and stalk yields obtained under this treatment.

Gross returns (` ha^{-1})

Gross returns differed significantly among nitrogen management treatments. T_8 recorded the highest gross returns (` 58,772 ha$^{-1}$), followed by $T_7$ (` 51,615 ha{†¹) and T_2 (` 51,070 ha$^{-1}$), whereas $T_1$ recorded the lowest gross returns (` 19,382 ha^{-1}). The higher gross returns under T_8 were primarily associated with its greater seed and stalk yields. The gross returns increased progressively with the higher nano-N concentrations when applied at both rosette and flowering stages, from ` 36,428 ha$^{-1}$ in $T_4$ to ` 58,772 ha^{-1} in T_8. In contrast, a single foliar application of nano-N @ 4 mL L^{-1} at flowering (T_3) generated ` 27,836 ha^{-1}. Lahari *et al.* (2021) similarly reported improved economic returns with integrated application of conventional nitrogen and foliar nano-nitrogen, particularly with 50% conventional N combined with nano-N @ 4 mL L^{-1}.

Net returns (` ha^{-1})

Net returns were significantly influenced by nitrogen management. T_8 recorded the highest net returns (`

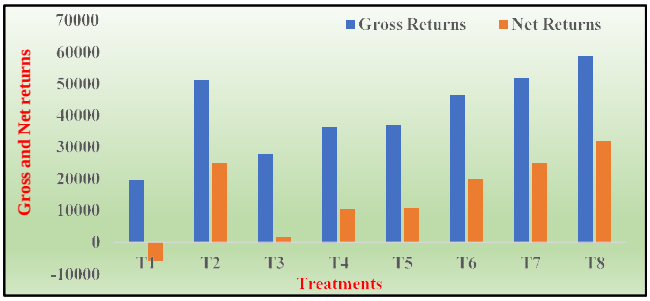


Fig. 3 : Influence of foliar application of nano urea on monetary returns of mustard.

nitrogen application. Similarly, Meena *et al.* (2017) reported favourable economic responses to nano-fertilizer application.

Benefit–cost ratio

The benefit–cost ratio (B:C) was significantly influenced by nitrogen management. T_8 recorded the highest B:C ratio (2.19), followed by T_2 (1.97) and T_7 (1.94). T_6 recorded a B:C ratio of 1.75, whereas T_4 and T_5 recorded 1.39 and 1.40, respectively. T_3 recorded 1.06, while the control treatment (T_1) recorded the lowest B:C ratio (0.77), indicating that the gross returns were insufficient to recover the cost of cultivation under the no-N treatment. The B:C ratio increased with increasing

Table 7 : Influence of foliar application of nano urea on monetary returns of mustard.

Treatments	Mustard economics			
	Cost of cultivation (Rs. ha^{-1})	Gross returns (Rs. ha^{-1})	Net returns (Rs. ha^{-1})	B-C Ratio
T_1 : No Nitrogen application	25188	19382	-5806	0.77
T_2: ½ RDN at sowing + 1/2 RDN at flowering	25968	51070	25102	1.97
T_3: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} atflowering	26178	27836	1658	1.06
T_4: ½ RDN at sowing + foliar spray of nano-N @ 2 ml L^{-1} atrosette stage and flowering	26178	36428	10250	1.39
T_5: ½ RDN at sowing + foliar spray of nano-N @ 2.5 ml L^{-1}at rosette stage and flowering	26328	36940	10612	1.40
T_6: ½ RDN at sowing + foliar spray of nano-N @ 3 ml L^{-1} atrosette stage and flowering	26478	46350	19872	1.75
T_7: ½ RDN at sowing + foliar spray of nano-N @ 3.5 ml L^{-1}at rosette stage and flowering	26628	51615	24987	1.94
T_8: ½ RDN at sowing + foliar spray of nano-N @ 4 ml L^{-1} atrosette stage and flowering	26778	58772	31994	2.19
SEm±	0.0	2652.9	2652.9	0.1
CD (p=0.05)	0.0	8046.2	8046.2	0.3
CV%	0.0	11.2	31.0	11.0

nano-N concentration when two foliar applications were made at the rosette and flowering stages. The two-spray treatments at 3, 3.5 and 4 mL L^{-1} recorded B:C ratios of 1.75, 1.94 and 2.19, respectively, compared with 1.39 and 1.40 at 2 and 2.5 mL L^{-1}.

Conclusion

The study demonstrated that nitrogen management through a combination of basal conventional nitrogen and foliar nano-urea application influenced the growth, biomass production, yield formation and economic performance of *rabi* mustard. The response became more pronounced when nano-urea was applied at both the rosette and flowering stages, indicating the importance of maintaining adequate nitrogen availability during active crop growth and reproductive development. Among the treatments, ½ RDN at sowing + foliar nano-urea @ 4 mL L^{-1} at rosette and flowering (T_8) consistently recorded higher plant height, LAI, dry matter accumulation and yield attributes. This treatment resulted in the highest seed yield (1126 kg ha^{-1}), stalk yield (1904 kg ha^{-1}) and harvest index (37.2%). It also generated the highest gross returns (` 58,772 ha$^{-1}$), net returns (` 31,994 ha^{-1}) and benefit: cost ratio (2.19). Under the specific agro-climatic and experimental conditions of the study, integrating basal conventional N with foliar nano-urea at critical growth stages showed potential for improving the productivity and economic performance of *rabi* mustard.

Acknowledgment

I am thankful to Professor Jayashankar Telangana Agricultural University for providing all the required facilities from the university.

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