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Influence of sowing methods and nano-urea supplementation on canopy development, biomass partitioning and seed yield of mustard (*Brassica juncea* (L.) Czern.)

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Abstract

Mustard (*Brassica juncea* (L.) Czern.) productivity in the Indo-Gangetic Plains is constrained by suboptimal agronomic practices and low nitrogen (N) use efficiency (NUE). A two-year field experiment was conducted during the rabi seasons of 2023–24 and 2024–25 at Integral University, Lucknow, Uttar Pradesh, India, to assess the effects of sowing method and foliar nano-urea application on mustard growth, biomass accumulation and seed yield. The experiment used a split-plot design with 3 sowing methods (ridge-furrow, flat-bed line sowing and broadcasting) in main plots and 4 N treatments in subplots: 100 % recommended dose of nitrogen (RDN) through urea, three nano-urea sprays without soil-applied urea, 75 % RDN through urea plus one nano-urea spray and 50 % RDN through urea plus 2 nano-urea sprays. Plant height, leaf area index (LAI), soil plant analysis development (SPAD) value, fresh and dry biomass and seed yield were recorded at 30, 60 and 90 days after sowing and at harvest. Flat-bed line sowing produced better canopy development and approximately 17–18 % higher seed yield than broadcasting, while ridge-furrow sowing showed intermediate performance. Full N application improved LAI, SPAD values and biomass production; however, replacing 25 % of urea N with 1 nano-urea spray maintained seed yield at 16.1–17.1 q ha^{-1}, comparable to full urea application. In contrast, nano-urea alone or a 50 % reduction in urea significantly reduced chlorophyll content, biomass and yield. Partial substitution of urea with nano-urea also improved apparent NUE. Overall, flat-bed line sowing combined with partial nano-urea substitution offers a promising strategy for improving mustard productivity and NUE.

Keywords: *Brassica juncea;* canopy; nitrogen management; productivity; sowing methods

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Introduction

Rapeseed-mustard is the third most important oilseed crop in the world after soybean (*Glycine max* (L.) Merr.) and palm (*Elaeis guineensis* Jacq.) oil. Among the 7 edible oilseeds cultivated in India, rapeseed-mustard (*Brassica* spp.) contributes 28.6 % of the total production of oilseeds (1, 2). However, mustard is

predominantly cultivated in marginal, rainfed environments of the Indo-Gangetic Plains (IGP), where suboptimal agronomic practices and nutrient deficiencies (especially nitrogen (N) deficiencies) limit its yield potential (3). One key factor affecting mustard productivity is the method of sowing. Traditional broadcasting of seed often results in uneven plant stands, intraspecific competition and poor resource utilisation (4). In contrast, line sowing on flat beds or raised ridges can improve crop establishment and create a favourable microenvironment for growth by ensuring optimal plant spacing and better root-zone conditions (5).

Prior studies have reported that planting mustard on raised beds or ridges significantly increases plant growth, water-use efficiency and yield compared with conventional flat or broadcast sowing. A recent study observed that raised-bed sowing enhanced mustard plant height, total dry matter and seed yield compared with flat sowing in the IGP (6). Under stress conditions such as soil salinity or waterlogging, ridge planting has been shown to substantially outperform conventional planting methods, increasing seed yield by up to 30–45 %. These findings underscore that sowing method is an important determinant of canopy development and yield in mustard-based systems.

Nitrogen nutrition is another critical factor for mustard growth and productivity. Indian mustard has a high N requirement, generally ranging from 100–120 kg N ha^{-1} for optimum growth and yield. However, the recovery of N from conventional urea fertilisers under farmers' field conditions is often low, with only about 20–50 % of the applied N being taken up by the crop, resulting in substantial N losses and reduced fertiliser-use efficiency (7). The remainder is lost through volatilisation, leaching and denitrification, causing environmental pollution (e.g., greenhouse gas emissions) and economic inefficiency (8). Improving nitrogen use efficiency (NUE) in mustard is therefore a priority for sustainable intensification.

In recent years, nano-fertilisers, such as nano-urea, have emerged as innovative alternatives to bulk fertilisers. Nano-urea is a colloidal fertiliser with extremely small N particles (on the order of nanometres) intended for foliar application. Due to its high surface area and targeted delivery to leaves, nano-urea can potentially enhance plant N absorption and reduce losses (9). Early research indicates that foliar nano-urea can maintain crop yields at substantially lower N application rates than conventional urea. For instance, trials in wheat, maize and millet have shown that 2 foliar sprays of nano-urea allowed a 25 % reduction in prilled urea N with no yield penalty. Similarly, in rice and wheat, replacing 25–50 % of recommended urea with nano-urea has been reported to preserve grain yields while boosting agronomic NUE (10).

Nano-urea offers a reduced environmental impact compared with conventional urea. Nano-urea has the potential to improve NUE by supplying N through foliar application and thereby reducing reliance on soil-applied urea; however, its use does not necessarily eliminate N losses through leaching or gaseous emissions. Despite these advantages, there is ongoing debate about the extent to which nano-urea can substitute for soil-applied N. Some studies caution that nano-urea alone cannot fully replace bulk urea for maximum yields and that combined use (integrated conventional and nano sources) is more effective (11). Mustard, in particular, may have a limited N uptake capacity at later growth stages, making the timing of N supply critical. Foliar nano-urea applied at appropriate phenological stages (e.g., rosette or flowering) could thus improve N uptake timing in mustard (12). However, field research on nano-urea in mustard is still in its infancy, with few studies quantifying its impact on mustard canopy growth, biomass partitioning or yield.

In this context, we hypothesised that optimising sowing method and N-fertilisation strategy in tandem would enhance mustard performance. Specifically, line sowing (flat or ridge) was expected to improve canopy development (leaf area, light interception) and yield over broadcasting and foliar nano-urea supplementation was expected to sustain mustard growth and yield even with reduced soil-applied N by improving NUE. To test these hypotheses, we conducted a 2-year field experiment in the IGP evaluating 3 sowing methods and 4 N management regimes (including partial replacement of urea with nano-urea sprays). The objectives were to assess the influence of sowing method on mustard canopy traits (plant height, LAI, chlorophyll index), biomass accumulation and yield and to determine the effectiveness of nano-urea foliar applications in maintaining crop performance under reduced urea-N inputs. The overall goal was to identify agronomic combinations that improve mustard N efficiency and productivity under the conditions of Uttar Pradesh.

Materials and Methods

Experimental site and design

Field experiments were conducted during two consecutive rabi (winter) seasons of 2023–24 and 2024–25 at the Agricultural Research Farm of Integral University, Lucknow, Uttar Pradesh, India. The site is situated in the IGP (approximately 26.8° N, 81.0° E, at an elevation of 120 m) and features a subtropical semi-arid climate with cool, dry winters. Each season's experiment was laid out in a split-plot design with 3 replicates. The main-plot factor was sowing method with 3 levels: S1–ridge-furrow sowing (raised-bed planting), S2–flat-bed line sowing and S3–broadcasting on a flat surface. For ridge sowing, seeds were sown on the top of 0.5 m wide ridges with furrows facilitating drainage, whereas flat sowing involved drilling seeds in lines on a level seedbed at a row spacing of approximately 30 cm. Broadcasting entailed scattering seed uniformly over the plot, followed by a light covering with soil.

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The subplot factor was N management, consisting of 4 treatments: N1-100 % recommended dose of nitrogen (RDN) applied as conventional urea, N2-3 foliar sprays of nano-urea (with no soil-applied urea), N3-75 % RDN as urea + 1 foliar nano-urea spray and N4-50 % RDN as urea + 2 foliar nano-urea sprays. The recommended N rate for mustard in this region is approximately 80 kg N/ha; thus, 100 % RDN corresponded to approximately 80 kg N/ha supplied through prilled urea (46 % N). In treatments with reduced urea, the remaining nitrogen was intended to be supplied via Indian Farmers Fertiliser Cooperative Limited (IFFCO) nano-urea (a liquid formulation containing 4 % N w/v). Each foliar nano-urea spray delivered approximately 40 g of N/ha in 500 mL of solution, following the manufacturer's guidelines. All plots (including those receiving nano-urea) were given uniform basal phosphorus (P) (40 kg phosphorus pentoxide (P_2O_5)/ha as single superphosphate) and potassium (K) (60 kg potassium oxide (K_2O)/ha as muriate of potash) at sowing to ensure these nutrients were non-limiting.

Crop management

Mustard seeds of the cultivar '*Pusa Kranti*' were sown and a standard seed rate of 6 kg/ha was used for line sowing and ridge sowing, while a slightly higher rate (approximately 6 kg/ha) was broadcast to account for uneven establishment. Subplots measured 4 × 3 m (12 m²). For N1 (100 % urea) subplots, urea was split-applied: half at sowing and half at the onset of stem elongation (approximately 30 DAS). In the integrated treatments (N3 and N4), the reduced urea doses were applied at sowing and nano-urea foliar sprays were applied at critical growth stages (30 DAS for the single spray in N3; 30 and 60 DAS for the 2 sprays in N4).

The nano-urea was applied using a hand-held knapsack sprayer to achieve uniform coverage of the foliage, typically during the morning hours with mild temperatures to maximise absorption. Standard agronomic practices were followed for all plots. Irrigation (if needed) was provided uniformly. In 2023–24, supplemental irrigation was applied at flowering, whereas in 2024–25, adequate residual soil moisture and timely winter rainfall meant that no irrigation was required. Weed control was done manually at 25 DAS. No major pest or disease incidence occurred; however, to control aphids, imidacloprid 17.8 % SL was sprayed. The crop was harvested in late February each year (roughly 120–130 DAS) when pods had turned yellow and seeds had achieved physiological maturity.

Observations and measurements

Canopy development was monitored by measuring plant height, leaf area index (LAI) and chlorophyll index at 30, 60 and 90 DAS and at harvest. Plant height was measured from the base to the apex of the main stem on 5 representative plants per plot. Leaf area index was determined using a plant canopy analyser (AccuPAR LP-80 ceptometer) by averaging readings taken at 3 random locations per plot (in broadcast plots, a 0.25 m² quadrat was used). The chlorophyll status of the leaves was assessed using a soil plant analysis development (SPAD) chlorophyll index value with a Minolta SPAD-502 metre; 10 readings were taken on the upper, fully expanded leaves per plot and averaged.

Additionally, destructive sampling was conducted to measure biomass. At each stage (30, 60 and 90 DAS), 2 plants were uprooted from each plot and their fresh weights were recorded. These plants were then oven-dried at 70 °C to constantly determine dry matter. At harvest, biomass partitioning was evaluated by separating the economic yield (seeds) from the straw. Grain yield was determined by harvesting the central 5 m² area of each subplot, threshing and drying the seeds to a moisture content of 8 % and then converting the yield to quintals per hectare (q/ha). The stover (dry aboveground residue after threshing) from the same area was weighed to compute total aboveground biomass. Harvest index was calculated as the ratio of seed yield to total above ground biomass.

$$\text{HI (\%)} = \frac{\text{Seed yield}}{\text{Biological yield}} \times 100$$

Data analysis

Data from each season were analysed separately due to slight year-to-year climatic variations, but the overall trends were comparable across years. Analysis of variance (ANOVA) for the split-plot design was performed using statistical analysis system (SAS) software, with means for the sowing method compared at the main-plot level and means for the N treatment compared at the subplot level. Fisher's least significant difference (LSD) at the 5 % probability level was used to test for significant differences between treatments. Since no significant sowing × N interaction was detected for any parameter, main effects are primarily reported and discussed.

Results

Canopy development: Plant height and leaf area index

The sowing method had a significant effect on mustard canopy size. By 60 DAS (onset of flowering), plants in flat-bed sowing (S2) were significantly taller (76.7 cm) than those under ridge sowing (72.9 cm) and broadcasting (68.8 cm). The height advantage of line-sown crops persisted to maturity. At 90 DAS, mustard on flat beds attained a height of approximately 148 cm, about 5–6 cm taller than broadcast crops (which reached approximately 142 cm), with ridge-sown plants intermediate at approximately 145 cm. These differences were statistically significant ($LSD_{0.05} \approx$ 1.2 cm at 90 DAS). By harvest, flat and ridge sowing produced similarly tall plants (approximately 148 and 146 cm, respectively), both exceeding the stature of broadcast plants (approximately 144 cm). The more favourable plant geometry in line sowing likely facilitated

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better early growth and stem elongation (13). In contrast, broadcasting led to uneven establishment and a slight reduction in plant height (14).

Nitrogen management exerted an even stronger effect on plant stature. Adequate N supply (100 % RDN) resulted in the tallest plants, while the nano-urea-only treatment (N2) produced noticeably shorter mustard plants (15). At 90 DAS, full urea fertilisation (N1) achieved a height of approximately 149 cm, significantly higher than the 142 cm under nano-urea alone (N2). Intermediate heights (approximately 144–146 cm) were recorded in the integrated treatments (N3, N4), which received some soil urea plus foliar nano-urea.

Fig. 1 illustrates the temporal height progression under each N regime. Initially, at 30 DAS, plant height was uniform (≈25–27 cm) across N treatments, since early growth relied on basal nutrients. Thereafter, differences became pronounced: by 60 DAS, N1 plants were approximately 77 cm in height, versus only approximately 70 cm in N2 (nano-urea only), reflecting faster bolting and canopy expansion with better nitrogen nutrition (16). The height trajectories of N3 (75 % urea + spray) and N4 (50 % urea + 2 sprays) closely trailed N1, indicating that foliar nano-urea partially compensated for reduced soil N. By harvest, N1 plants reached approximately 150 cm, about 8 cm taller than N2 plants (142 cm). Statistically, N omission (N2) significantly reduced final plant height, whereas N3 and N4 were not drastically different from N1. These results suggest that supplemental nano-urea could sustain near-optimal vegetative growth up to a point (75 % substitution), beyond which height and vigour declined under N shortfall.

Leaf area index trends mirrored those of plant height. It increased rapidly from 30–90 DAS in all treatments, peaking around the time of flowering. The sowing method had a significant influence on LAI primarily at later stages. By 90 DAS, flat-sown mustard achieved the highest LAI (approximately 3.27), followed by ridge sowing (approximately 3.03), while broadcast crops had a significantly lower LAI (approximately 2.56). The $LSD_{0.05}$ for LAI at 90 DAS was 0.38, indicating that the approximately 0.7-unit LAI gap between flat and broadcast sowing was meaningful. The denser foliage in line-sown plots can be attributed to more uniform plant spacing and possibly greater light interception (17). Ridge sowing also outperformed broadcasting in LAI, although the difference between ridge and flat sowing was slight (3.03 vs. 3.27, not statistically significant). By harvest, the LAI declined as plants senesced and pods matured (LAI of approximately 1.2–1.3 across sowing methods, with negligible differences). Thus, the main canopy advantage of line sowing manifested during the mid-season, when leaf area development is critical for biomass production.

Nitrogen availability had a pronounced impact on LAI development (Fig. 2). All treatments started with low LAI (approximately 0.25) at 30 DAS, but divergence occurred by the flowering stage. Plots receiving full N (N1) recorded LAI of approximately 3.6 at 90 DAS, significantly higher than the LAI of approximately 2.6 under N2 (nano-urea only). Moderate LAI values (approximately 2.8) were observed for N3 and N4. The ANOVA confirmed that at 90 DAS, LAI in N1 was substantially greater than in the nano-urea-supplemented treatments ($LSD_{0.05}$ ≈ 0.34; N1 vs. N2 difference = 0.99). Essentially, mustard that received only foliar nano-urea (N2) experienced N deficiency symptoms by flowering, resulting in sparser canopy cover. By contrast, supplying even 50–75 % of the recommended urea (N4, N3) allowed LAI to approach 78–80 % of that of the fully fertilised crop (18). This trend suggests that while nano-urea contributed to leaf growth, it could not fully compensate for a significant reduction in soil N. At harvest, LAI values converged (approximately 1.1–1.3) as pods replaced leaves and any late green area differences were minor (differences at harvest were not significant for either factor). Overall, optimal N nutrition (N1) produced the lushest canopy, whereas N stress (especially in N2) curtailed leaf area expansion, aligning with known positive correlations between N rate, leaf chlorophyll and LAI in cereals and oilseeds (19).

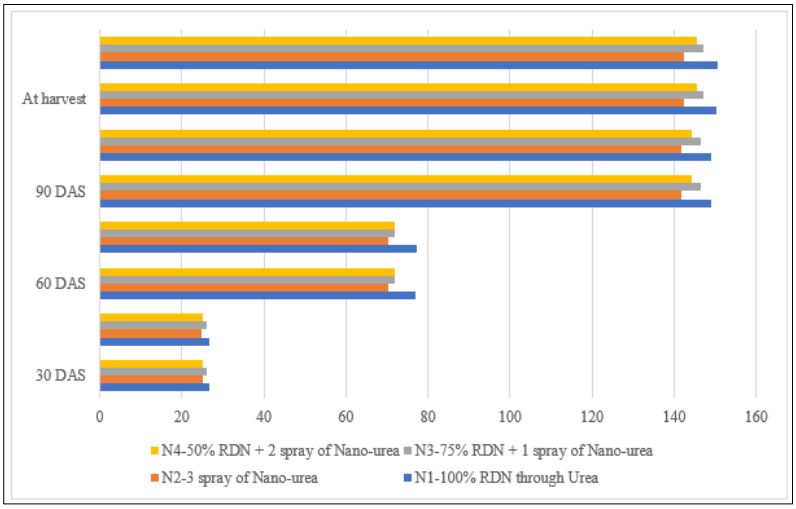


Fig. 1. Effect of nitrogen application on plant height (cm) at pooled. RDN: recommended dose of nitrogen; DAS: days after sowing.

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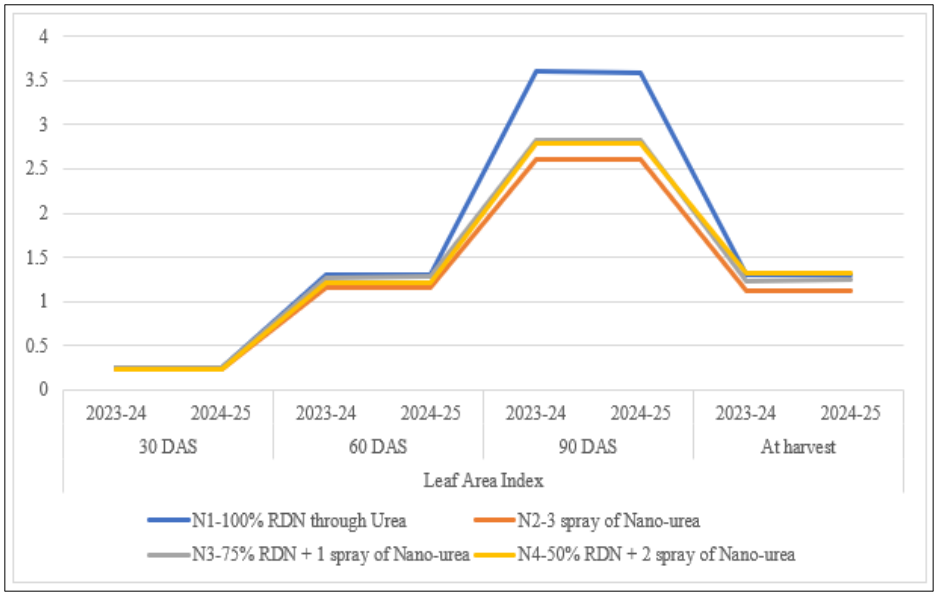


Fig. 2. Effect of nitrogen application on leaf area index (LAI) at pooled.

Chlorophyll content (SPAD) and canopy greenness

Chlorophyll meter (SPAD) readings provided an index of crop N status and photosynthetic potential (20). Sowing method per se did not significantly affect SPAD values at most growth stages (there were no consistent differences in leaf greenness attributable to ridge vs. flat vs. broadcast sowing). For instance, at 60 DAS, the SPAD values were roughly 30–31 in flat plots and 28–29 in broadcast plots, but the variation was within experimental error (no significant main-plot effect). Any minor trends suggested that better-managed sowing (line methods) could support slightly higher chlorophyll levels due to improved nutrient uptake, but these trends were subtle. By harvest, SPAD readings dropped to approximately 12 in all treatments as leaves senesced, with the sowing method showing no significant effect (all readings were nearly equally low). Thus, canopy greenness was primarily governed by N treatment rather than planting geometry.

Nitrogen management had a marked influence on SPAD at 60, 90 DAS and even at physiological maturity (Fig. 3). At flowering (60 DAS), fully urea-fertilised mustard (N1) had dark green foliage (mean SPAD of approximately 33), significantly higher than the pale green leaves in N2 (SPAD of approximately 27). The intermediate N regimes (N3, N4) showed SPAD values of approximately 30–31, falling between N1 and N2. By 90 DAS, N1 plots maintained the highest chlorophyll index (≈39.7 SPAD units), whereas N2 plots lagged at approximately 34.7. Notably, the SPAD difference of approximately 5 units between N1 and N2 at 90 DAS was highly significant ($LSD_{0.05}$ of approximately 1.8). Even N3 and N4 leaves had SPAD values (approximately 37.2 and 35.2 respectively) that were 2–4 units lower than those of N1, indicating that some mild N deficiency affected those treatments by the late season. Differences persisted into the grain-filling period: at harvest, the residual green leaf SPAD in N1 (≈14.3) was higher than in N3 (11.7) or N4 (11.2), with N2 being the lowest (approximately 11.0). Although absolute SPAD values were low at maturity, the trend suggests that N1 plants retained slightly more leaf N (delayed senescence) compared with the other treatments. The consistently lower SPAD in N2 at all stages confirms that relying solely on foliar nano-urea resulted in inadequate N in plant tissues, as reflected by chlorophyll content (21). Meanwhile, the near-parity of N3 (75 % urea + nano) with N1 until 60–90 DAS implies that a single nano-urea spray at a critical stage (here likely 30 DAS) effectively alleviated N stress early on, but by 90 DAS, a gap appeared, perhaps as the limited soil N became exhausted. Overall, the SPAD measurements corroborate the LAI and height data: ample soil N is required to achieve maximum canopy greenness and while nano-urea supplements improved leaf N status relative to the zero-urea scenario, they could not fully match the continuous N supply of conventional fertilisation (22). These findings are in agreement with recent research noting that nano-urea application can improve foliar N content and chlorophyll, but optimal results often occur when nano-fertilisers are used in conjunction with a baseline of conventional N.

Biomass accumulation and partitioning

Dry matter growth

The accumulation of biomass reflected the combined effects of canopy size and N availability. Across all treatments, mustard dry weight per plant increased slowly until 30 DAS, then rapidly during the 30–90 DAS window and finally plateaued as the crop matured by approximately 120 DAS (Fig. 4). The sowing method influenced total biomass primarily through the final plant population and size. Broadcast plots tended to have slightly lower dry matter per plant at harvest (on average 61.9 g/plant) compared with flat (66.5 g) and ridge (63.5 g) sowing. However, due to the slightly higher plant density often resulting from broadcasting, the total

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biomass per unit area did not differ as sharply. Still, the trend of the highest per-plant biomass in flat sowing suggests efficient resource capture and growth. By harvest, flat-sown plants produced approximately 7–8 % more dry mass than broadcast ones (significant at $p < 0.05$), while ridge-sown plants were intermediate. Notably, at mid-season (90 DAS), flat sowing already showed a biomass lead (29.4 g dry weight/plant vs. 27.2 g in broadcast), consistent with its higher LAI and plant height. Ridge planting did not significantly differ from flat planting in biomass at 90 DAS; however, by harvest, flat planting had a slight edge, indicating perhaps better seed filling or reduced abiotic stress (23).

The N treatments resulted in significant differences in biomass accumulation. Fig. 5 shows that plants with full N (N1) accumulated dry matter faster and to a greater final amount than N-deficient treatments. At 60 DAS, N1 plants had approximately 14.1 g dry weight, compared with only approximately 11.9 g in N2 (nano-only). This 19 % biomass gap widened by 90 DAS: N1 reached 30.7 g, whereas N2 stalled at 26.5 g (14 % lower). By maturity, the total dry weight per plant in N1 (71.3 g) was approximately 20 % greater than in N2 (59.6 g). The treatments with partial urea (N3, N4) achieved intermediate biomass. N3 (64.2 g) was only approximately 10 % lower than N1 at harvest and not statistically different, whereas N4 (60.7 g) was approximately 15 % lower than N1 and comparable to N2. These trends indicate that reducing urea-N beyond 50 % caused a marked decline in total crop biomass, even when supplemented with nano-urea. By contrast, a 25 % urea reduction (N3) had a relatively minor impact on final biomass, suggesting that one timely nano-urea spray could successfully augment plant N uptake to support near-maximal growth (24). The absence of any significant sowing × N interaction for dry weight implies that these N effects were consistent regardless of sowing method.

Fresh weight and partitioning

Patterns of fresh biomass (which includes water content) were similar to those of dry weight, with a few notable exceptions. At harvest, the average fresh weight of an individual mustard plant was highest under flat sowing (approximately 487 g/plant), followed by ridge sowing (approximately 455 g) and lowest under broadcasting (approximately 412 g). These differences in fresh weight were slightly more pronounced (flat plants were approximately 18 % heavier than broadcast plants on a fresh-weight basis) and all pairwise differences were statistically significant ($LSD_{0.05} \approx 22$ g). The greater fresh mass in line-sown crops could be due to both higher structural biomass and possibly higher water retention in their tissues at harvest (owing to better hydration or thicker stems) (25). In terms of biomass partitioning, all treatments had comparable harvest indices (approximately 0.25–0.27, calculated from seed and total biomass data), indicating that the proportion of biomass allocated to seeds vs. stover was not drastically altered by sowing method or N treatment. On average, seed yield constituted approximately 26 % of aboveground dry biomass in well-fertilised plots. Nitrogen shortage (N2) slightly reduced the harvest index (to approximately 25 %) because vegetative parts (stover) were not much smaller, whereas seed formation was more curtailed. In contrast, ample N (N1) and moderate N (N3) produced a slightly higher grain yield per unit biomass, suggesting a more efficient conversion of growth into yield.

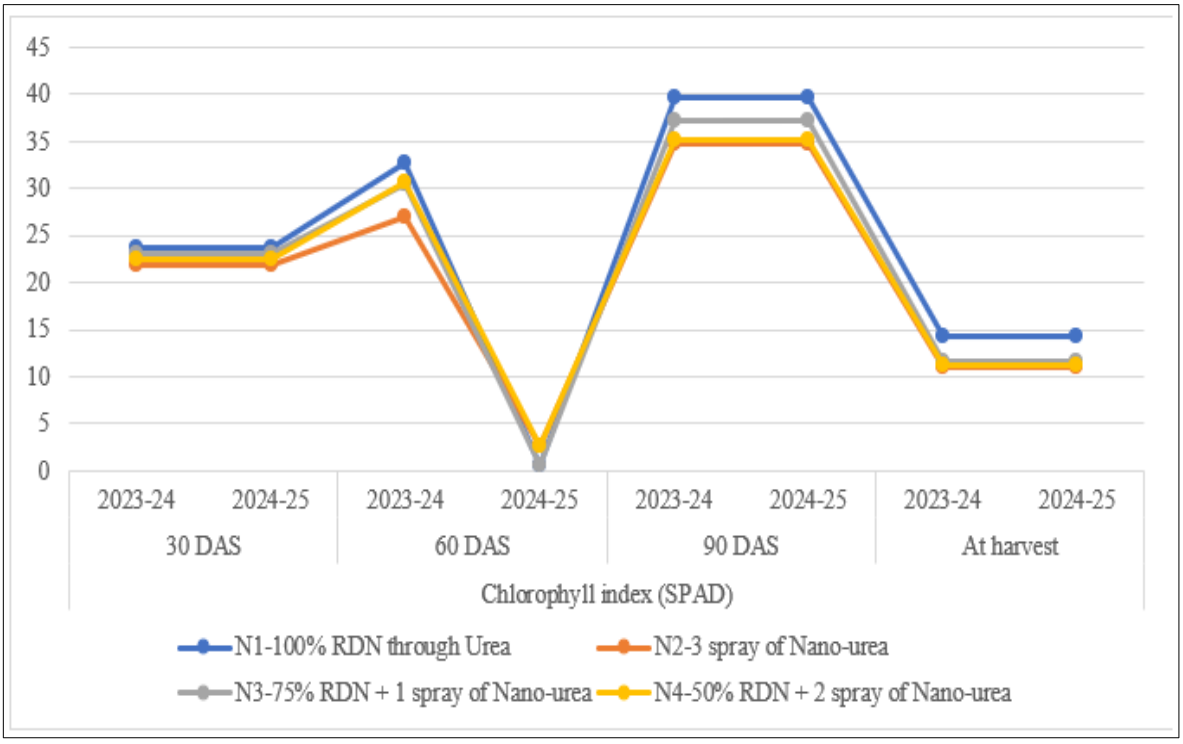


Fig. 3. Effect of nitrogen application on chlorophyll content (SPAD) at pooled.

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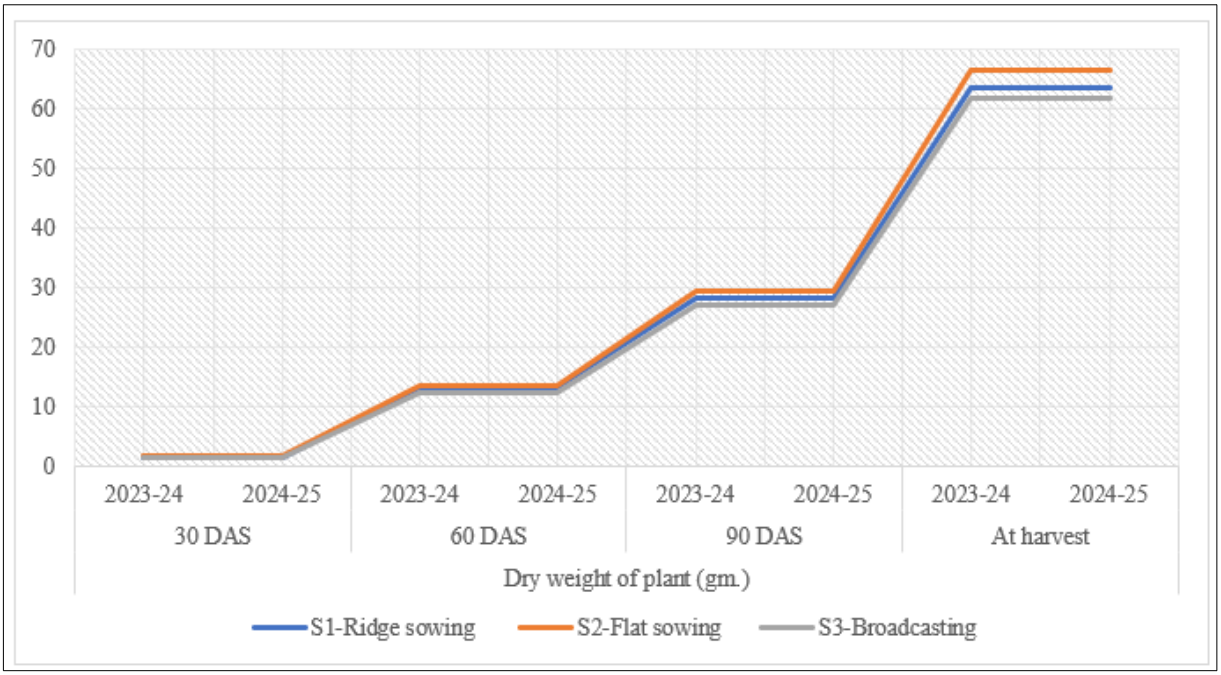


Fig. 4. Effect of sowing methods on dry weight (g) at pooled.

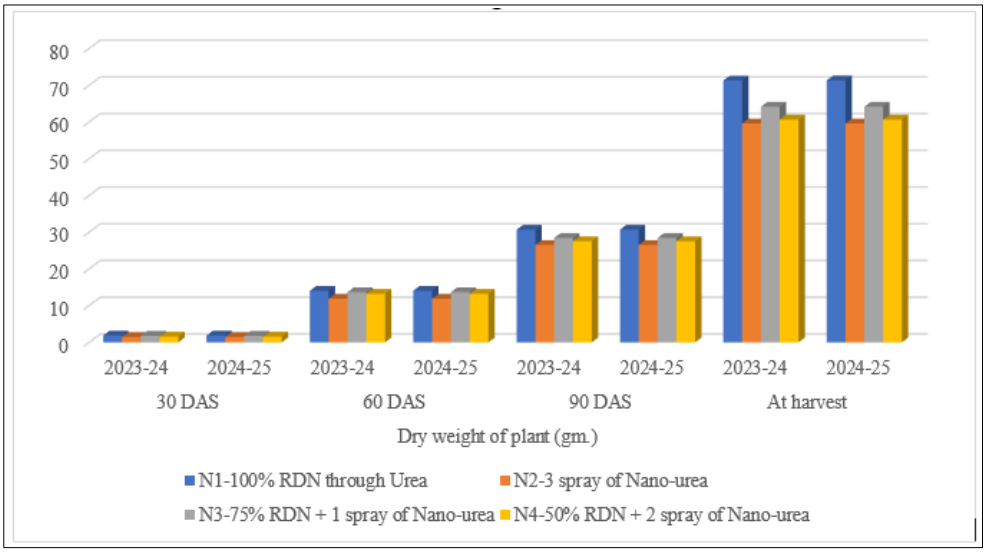


Fig. 5. Effect of nitrogen application on dry weight (g) of plant at pooled.

Seed yield

Grain yield outcomes integrated the effects of both agronomic factors. Sowing method had a clear impact on mustard seed yield (Fig. 6, Table 1). The highest yields were obtained with flat-bed line sowing, which produced 17.2 q/ha in 2023–24 and 17.19 q/ha in 2024–25. Ridge-furrow sowing yielded slightly lower results (16.2 q/ha in both years), while broadcasting resulted in the lowest yields at approximately 14.66 q/ha. The yield advantage of line sowing over broadcasting was substantial–flat sowing exceeded broadcasting by approximately 2.5 q/ha (≈17 % higher) consistently in both years. Ridge sowing also out-yielded broadcasting by about 1.5 q/ha (≈10 %), whereas the difference between ridge and flat was smaller (approximately 1.0 q) and not significant at $p < 0.05$ in one year. Statistically, the main-plot effect of sowing method on yield was significant ($LSD_{0.05}$ of approximately 0.3 q/ha); flat sowing was superior to broadcasting ($p < 0.01$) and marginally better than ridge sowing. These results confirm that proper line placement of mustard seed is beneficial for yield formation (26). Likely reasons include more uniform plant distribution and nutrient uptake, resulting in improved growth and yield components (e.g., number of pods per plant and seeds per pod) as observed anecdotally during crop sampling. Broadcasting, in contrast, can lead to overcrowded patches and gaps,

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resulting in suboptimal resource utilisation and, consequently, lower collective yield (27). Notably, the ridge method–which often benefits crops under waterlogged or resource-constrained conditions–did not outperform flat sowing here, possibly because water conditions were adequate and flat sowing achieved a higher effective plant population density. Nonetheless, both ridge and flat methods clearly outperformed the broadcast method in terms of seed yield. These findings are in line with earlier reports from the region that improved planting techniques (line or ridge planting) enhance mustard yield by ensuring better light interception and root growth (28).

Nitrogen management exhibited a strong influence on seed yield (Fig. 7). The treatment receiving 100 % RDN through urea (N1) achieved the highest yield, averaging 17.12 q/ha over the 2 years. In contrast, the nano-urea-only regime (N2) yielded the lowest amount at approximately 15.07 q/ha, indicating a significant yield penalty (approximately 12 % below N1) when no conventional urea was applied. The integrated treatments showed intermediate performance: N3 (75 % urea + 1 nano spray) yielded 16.16 q/ha, only about 6 % lower than full urea, whereas N4 (50 % urea + 2 nano sprays) yielded 15.72 q/ha, about 8–9 % lower than N1. Statistical comparisons ($LSD_{0.05}$ of approximately 0.90 q/ha) revealed that N1 and N3 were on par (the approximately 0.97 q difference was just at the significance threshold), indicating that a 25 % reduction in soil N supplemented with a foliar spray did not significantly diminish yield. N4 and N2, however, were both significantly lower than N1 (by approximately 1.4 and 2.0 q, respectively, $p < 0.05$). Yields of N4 and N2 were also slightly lower than N3 (though N4 vs. N3 was not statistically significant). These yield outcomes demonstrate that foliar nano-urea can partially substitute for basal urea-N without major yield loss up to a point (here, 25 % replacement was feasible, whereas 50 % caused a moderate yield drop) (11). Three nano sprays in N2 could not compensate for the complete absence of soil N, resulting in markedly reduced yield, which underscores that nano-urea alone is insufficient for maximising mustard yield potential (15). Indeed, our result that N2 (nano-only) yielded approximately 2 q/ha less than N1 aligns with recent findings that nano-urea, while enhancing N uptake, cannot single-handedly replace the bulk of N fertiliser required for full yield realisation. On the positive side, N3's near-equivalent yield to N1 suggests improved NUE: the crop produced almost the same output with 25 % less total N input. This implies a higher agronomic efficiency (yield per unit N) for the integrated nano-urea approach (29).

Fig. 8 represents mustard seed yield across treatments (mean of 2023–24 and 2024–25). (A) Effect of sowing method on seed yield (quintals per hectare). Line sowing on flat beds achieved the highest yield, followed by ridge sowing, while broadcasting was lowest. (B) Effect of N management on seed yield. Full recommended N (100 % urea) and 75 % urea + nano spray produced similar yields, whereas yield declined with 50 % urea (2 nano sprays) and was lowest with nano-urea alone. Error bars represent ± SE. Within each panel, means of different letters (not shown) would be significantly different at the 5 % level.

It is noteworthy that the yield trends were highly consistent across the 2 study years, as indicated by the nearly overlapping year-wise values (Fig. 8). There was no significant year × treatment interaction, meaning that each treatment ranked similarly in both 2023–24 and 2024–25. Seasonal weather variations (slightly cooler, drier winter in 2024–25) did not appreciably alter the response patterns, attesting to the robustness of the findings. The overall site mean yields (approximately 16 q/ha) were in line with regional yields for mustard under good management, suggesting that the experiment's outcomes are representative of the region's typical conditions.

Table 1. Effect of sowing methods and nitrogen management on seed yield

Treatments	Seed yield (q/ha)	
	2023–24	2024–25
Main plots (method of sowing)		
S_1-ridge sowing	16.19	16.20
S_2-flat sowing	17.21	17.19
S_3-broadcasting	14.66	14.66
SEm±	0.08	0.07
C.D. (0.05)	0.30	0.28
Subplots (nitrogen management)		
N_1-100 % RDN through urea	17.13	17.11
N_2-3 spray on nano-urea	15.07	15.07
N_3-75 % RDN + 1 spray on nano-urea	16.16	16.16
N_4-50 % RDN + 2 spray on nano-urea	15.72	15.72
SEm±	0.31	0.30
C.D.(0.05)	0.91	0.89
All interactions (C.D.= 0.05)	NS	

RDN: recommended dose of nitrogen.

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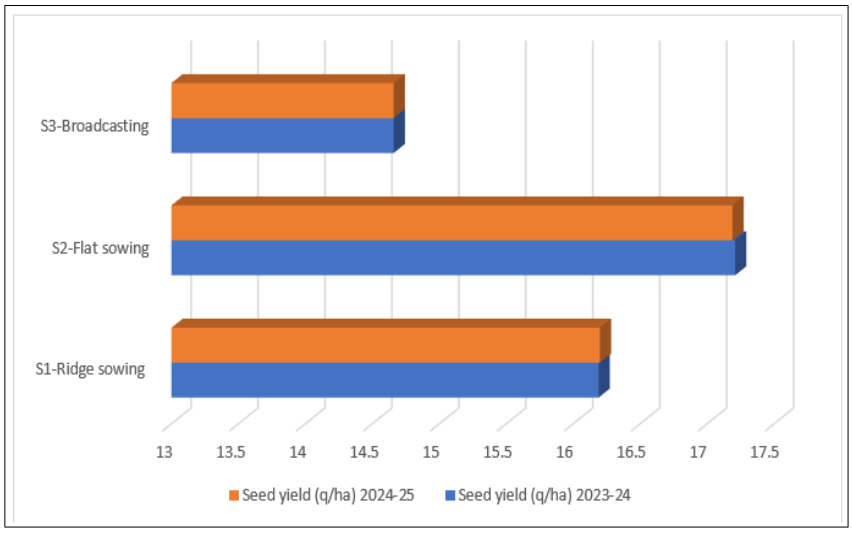


Fig. 6. Effect of sowing methods on seed yield (q/ha).

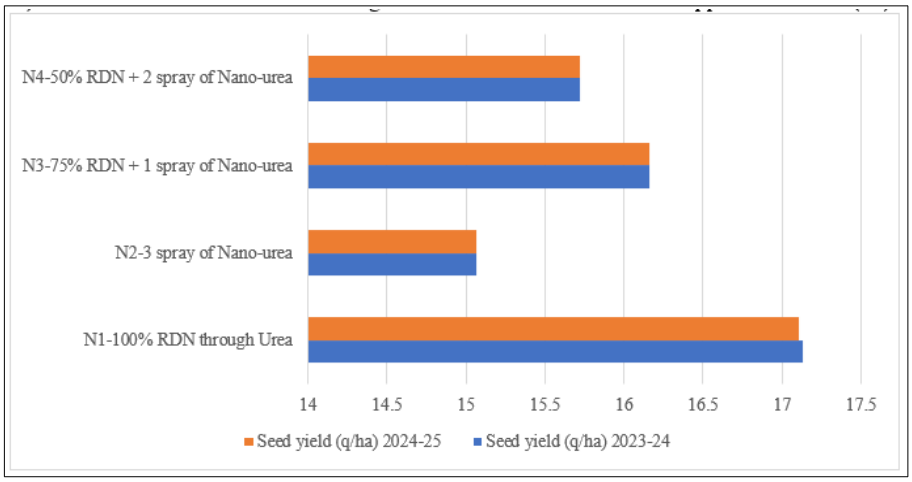


Fig. 7. Effect of nitrogen application on seed yield (q/ha). RDN: recommended dose of nitrogen.

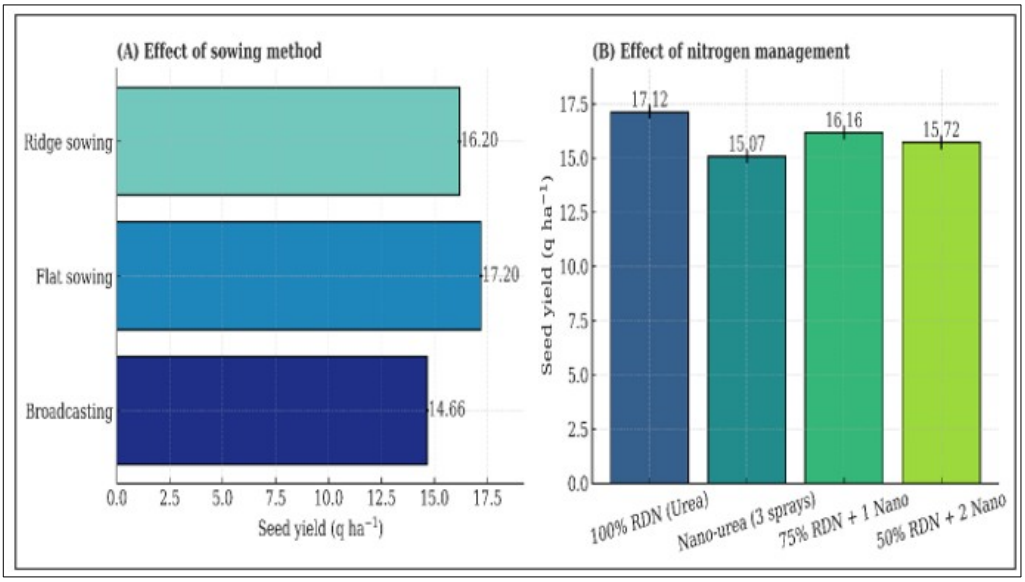


Fig. 8. Effect of sowing methods and nitrogen application on seed yield (q/ha) at pooled.

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Discussion

This two-year field study demonstrated that both sowing method and N fertiliser management profoundly affect canopy development, biomass accumulation and yield in mustard grown across the IGP. The results highlight that optimising physical planting techniques and adopting nano-urea-based fertilisation can be synergistic strategies for improving mustard productivity and N efficiency.

Sowing method effects

The clear yield superiority of line sowing either on flat beds or ridges over the traditional broadcasting method confirms the importance of proper crop geometry in mustard. Broadcasting, while easy to implement, led to suboptimal stand establishment characterised by plant clustering and uneven growth, which ultimately translated into a sparser canopy (lower LAI) and reduced seed yield. In contrast, row planting ensured a more uniform distribution of plants, reducing intra-specific competition for light, moisture and nutrients (27). By 90 DAS, line-sown crops had significantly greater LAI and biomass than broadcast crops, indicating more effective canopy light interception and photosynthetic area. These findings concur with earlier agronomic studies in oilseed brassicas. For instance, in black mustard (*B. juncea*), ridge/raised-bed sowing produced higher plant height, dry matter accumulation and seed yield than conventional flat sowing or broadcasting (23). Ridge sowing can provide additional benefits under certain conditions by improving root zone aeration and drainage (30). In our study, ridge plots indeed showed improved performance over broadcast sowing, with a 10 % yield increase. However, flat-bed line sowing marginally out-yielded ridge sowing here. One reason could be that the experimental seasons did not experience waterlogging or salinity stress, under which ridges usually confer advantages, so the ridge benefit was not fully expressed. Meanwhile, flat sowing allowed a slightly higher planting density and conserved soil moisture better than ridges, which dry out faster in a rainfed system, thereby supporting equal or greater biomass and yield (31). Another factor may be that ridge creation in our plots slightly disturbed uniformity or caused minor nutrient redistribution, whereas a flat seedbed maintained homogeneity (32). Regardless, both line-sown treatments surpassed broadcasting, reinforcing recommendations that line sowing is a “best practice” for mustard cultivation in the IGP. Adopting line sowing with appropriate row spacing of approximately 30 cm facilitates mechanisation, inter-row weeding and precision fertilisation and enhances resource-use efficiency, ultimately leading to improved yield and profitability for farmers.

Nitrogen management and nano-urea

Our findings align with this: the fully fertilised treatment with an N : P ratio of 80 : 60 : 40 produced the largest canopy and highest yield, while any N reduction tended to decrease these metrics. However, the critical observation is that the treatment with a 25 % reduction in the RDN (75 % RDN + 1 nano spray) yielded nearly the same amount as the 100 % urea treatment. This suggests that the foliar nano-urea was able to effectively deliver N to the plants at a key growth stage, compensating for the reduction in basal N. It is likely that the single nano-urea spray applied at 30 DAS, around the rosette stage, coincided with the peak crop N demand, thereby boosting plant N status when soil N became limiting. This aligns with the recommendation that, in N-limited scenarios, applying N at the rosette stage is crucial for mustard to improve its NUE (11). By contrast, when 50 % of the RDN was omitted and replaced with 2 nano sprays, we observed a modest yield penalty (approximately 8 %). Two sprays at 30 and 60 DAS provided more foliar N; however, 50 % basal N was apparently below the threshold needed to support maximum yield potential. Mustard’s peak N uptake period is the relatively early flowering stage and even though foliar feeding supplies N quickly to leaves, the total quantity of N provided via 2 nano sprays, approximately 80–100 g N per ha in our case, was far less than the 60 kg N/ha omitted from soil application. Thus, the crop likely experienced an N shortage during critical yield formation, despite foliar supplementation. This outcome resonates with a recent Public Library of Science (PLOS). One study reported that a combination of nano-urea with conventional urea was most effective –specifically, using nano-urea to replace 25 % of prilled urea did not impair yields of wheat, maize, mustard and pearl millet, whereas higher replacement levels could start to depress yields (33). Nano-urea’s strength lies in its high uptake efficiency; according to manufacturer reports, up to 80 % of foliar-applied N is absorbed and it can rapidly correct incipient deficiencies. Yet, its absolute N contribution per application is low because of the low total N content applied, so it functions best as a supplement to soil N, not an outright substitute for the bulk of the crop’s requirement. Our nano-only treatment N2 starkly illustrates that these 3 foliar sprays, even if efficiently absorbed, could not supply enough N for the developing yield sink, resulting in significantly reduced biomass and yield. By maturity, N2 plants had thinner stems, fewer branches and more premature leaf senescence, as well as lower SPAD values, all of which were symptomatic of N deficiency and were reflected in an approximately 12 % yield loss relative to the fully fertilised control.

An important implication of these results is the improved NUE under integrated fertilisation. The N3 treatment achieved approximately 94 % of the maximum yield with only 75 % of the N input. In other words, the agronomic efficiency (grain yield increase per kg of N applied) was higher in N3 than in N1. This suggests that foliar nano-urea can enhance the effectiveness of each unit of soil-applied N, perhaps by ensuring that N is available exactly when and where the crop most needs it, through leaf uptake during critical growth windows. Additionally, nano-urea may reduce losses–foliar application bypasses soil pathways for leaching or volatilisation, thereby retaining more N in the plant–soil system (8). Over two seasons, our N3 treatment consistently maintained yields. Reducing soil-

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applied urea-N by 25 % and supplementing it with 1 foliar nano-urea spray maintained seed yield statistically comparable to that under the full recommended N treatment. Recent economic analyses have indeed found higher benefit–cost ratios when a portion of conventional urea is replaced by nano-urea in mustard fertilisation. These findings were previously reported (34). Our findings reinforce that adopting nano-urea in an integrated manner can be advantageous without sacrificing yield.

It should be noted that while nano-urea shows promise, it is not a cure. The inability of nano-urea alone to support high yields underscores the need for a balanced approach. As evidenced by previous researchers, the manufacturers' claim that one bottle of nano-urea can replace an entire 45 kg bag of prilled urea is not substantiated by rigorous trials (35). In wheat, studies have found that nano-urea cannot fully substitute for prilled urea due to its lower absolute N content and complete replacement is not economically feasible (9). Our study echoes this for mustard–complete reliance on nano-urea led to suboptimal yields. However, a paradigm of conjunctive use of conventional and nano-fertilisers appears to be a sustainable path forward. By supplying a portion of N through soil to meet the base demand and build yield potential and a portion through foliar nano-urea to fine-tune N supply and minimise waste, farmers can potentially achieve the twin goals of productivity and efficiency. This integrated nutrient management strategy is in line with climate-smart agriculture approaches for the IGP, which emphasise precision nutrient delivery and reduce excess fertiliser use.

Crop physiology under treatments

The physiological measurements help explain the yield outcomes. Ample N (N1) led to more vigorous vegetative growth (taller plants, higher LAI) and higher chlorophyll content, all of which contribute to greater photosynthetic capacity and dry matter production. These crops had prolonged greenness (higher SPAD at 90 DAS and even at maturity), indicating delayed leaf senescence and continued assimilation that likely contributed to grain filling. Conversely, nano-urea-only crops (N2) showed an early onset of N stress–by 60 DAS, their SPAD was significantly lower and many leaves turned pale or yellow soon after flowering, reducing the effective photosynthetic leaf area. This premature senescence curtailed the source capacity to support the developing sink; fewer or smaller seeds were observed and field observations noted more shrivelled seeds in N2 pods. The integrated treatments N3 and N4 were intermediate; they experienced some N shortage, but later in the season. For example, N4 with 2 sprays remained nearly as green as N1 up to flowering, but towards maturity, SPAD levels dropped closer to those of N2, suggesting that by the grain-filling stage, the limited total N had become a constraint. Thus, while yield reduction in N4 was moderate, its lower harvest index compared with N1 indicates slightly inefficient translocation to seeds under nitrogen limitation. Sowing method, interestingly, did not directly affect SPAD (i.e., leaf N concentration) because all plots of a given N treatment received the same fertilisation. However, better growth in line-sown plots likely facilitated better uptake of available N, as indicated by the higher LAI and biomass observed in those plots. The net effect was that line-sown mustard could better realise the benefits of the fertiliser applied, whereas broadcast crops, even when fertilised, could not convert as much of that N into yield due to stand inefficiencies (36). This is supported by the observation that broadcast plots had slightly more lodging and mutual shading, which can lower photosynthetic efficiency and yield. Meanwhile, ridge plots had good uptake but perhaps slightly less water availability at certain times, which might have limited their seed set relative to flat plots despite similar biomass–a hypothesis consistent with the fact that ridge plants were marginally shorter and had slightly less dry weight than flat plants at harvest in our study.

Implications for Indo-Gangetic Plains agriculture

Our findings carry practical significance for mustard cultivation in South Asia. First, the yield gains from switching to line sowing, with an increase of as much as 2–3 q/ha over broadcasting, are economically meaningful for farmers and can be achieved with minimal additional cost – in fact, line sowing can be done via a seed drill, saving on seed rate and labour. This should encourage extension efforts to move farmers away from broadcasting towards drill sowing or ridge planting, which also enables easier intercultural operations. Second, the successful use of nano-urea to replace a quarter of the conventional N fertiliser suggests that nano-fertiliser technology can contribute to more sustainable nutrient management. In regions where urea is often overused, resulting in NUE values below 30 %, integrating nano-urea could allow for a reduction in total N applied, thereby mitigating environmental externalities without harming yields. This is particularly relevant in the IGP, where intensive cereal–oilseed systems have led to nitrate leaching and pollution. By reducing urea usage by 25 % and assuming no yield loss, farmers effectively reduce fertiliser consumption. Additionally, the foliar application of nano-urea aligns well with precision farming frameworks; it can be timed based on crop needs, guided, for example, by sensor-based N diagnostics for more efficient feeding. Our study also underlines that further reduction beyond 50 % may not be advisable in mustard unless accompanied by other innovations, such as improved nano-formulations or hybrids with higher N uptake. Interestingly, the results encourage a rethink of the recommended N dose: if 75 % of the traditional N can produce equivalent yields with nano-urea augmentation, extension recommendations could be adjusted to reflect this, pending validation across more sites and seasons.

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Conclusion

Improved sowing methods and nano-urea supplementation had a significant influence on the growth and productivity of Indian mustard in our 2-year study. Line sowing, especially on flat beds, proved superior to broadcasting by enhancing canopy development, increasing leaf area index (LAI) and plant stature and increasing seed yield by up to 17 %. Ridge-furrow sowing offered yield benefits over broadcasting as well, though it was slightly less productive than flat sowing under the given conditions. These results suggest that broadcasting could be replaced with row-based planting to improve mustard productivity under conditions similar to those of the present study. Nano-urea demonstrated considerable promise as a supplementary N source. Reducing soil-applied urea-N by 25 % and supplementing it with 1 foliar nano-urea spray maintained seed yield statistically comparable to the full recommended N treatment. Even a 50 % urea replacement with 2 nano-urea sprays sustained a high proportion of yield (≈92 % of full N yield), though with some penalties in biomass and chlorophyll. In contrast, sole reliance on nano-urea (no soil urea) was insufficient, underscoring that nano-urea is best used as an enhancer rather than a complete substitute. The optimal nitrogen (N) management for mustard in the Indo-Gangetic Plains (IGP) may therefore involve a combination of basal urea to meet fundamental crop N needs and strategic foliar nano-urea applications to fine-tune N supply and reduce total fertiliser requirement. This integrated approach achieved near-maximal yields in our study while reducing N input by 25 %, a win-win for farm economics and the environment. In practical terms, farmers may consider flat-bed line sowing and integrated urea-nano-urea application; however, these recommendations require validation across multiple locations, seasons and production environments before wider adoption. Wider implications include a lower risk of nitrate pollution and greenhouse gas emissions from mustard fields adopting nano-fertilisation. To solidify these findings, further multi-location trials and long-term studies are suggested, examining different cultivars and variable climatic scenarios. Moreover, research into the mechanisms of nano-urea uptake and its interaction with plant physiology will help refine usage guidelines. Overall, our study contributes evidence that modern agronomic practices-precision sowing and nano-fertilisation-can significantly improve mustard production in Uttar Pradesh and similar agro-ecologies, fostering a more sustainable and efficient agricultural system.

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Authors' contributions

BS conducted the investigation and laboratory analysis. BS, A and DSS contributed to conceptualisation. BS and A were responsible for data curation. BS and PS contributed to the methodology. BS, DSS, P, J and SG provided the resources. BS, PP, MK, MD, SD and AG contributed to writing the manuscript. DSS, PKW, NP and SS contributed to manuscript review and editing. All authors read and approved the final manuscript

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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