



RESEARCH ARTICLE

# Plant growth regulators as a strategy for growth and yield optimization of Indian mustard (*Brassica juncea* L.) under different agri-horticultural systems

Soumya Prakash Bhoi<sup>1</sup>, Sanjay Singh Rathore<sup>1</sup>, Kapila Shekhawat<sup>1</sup>, Puspa Parameswari<sup>2\*</sup>, Rahul<sup>3</sup>, Dileep Meena<sup>1</sup> & Parmeswar Dayal<sup>1</sup>

<sup>1</sup>Division of Agronomy, Indian Agricultural Research Institute, Pusa Campus 110 012, New Delhi, India

<sup>2</sup>Department of Agronomy, Punjab Agricultural University, Ludhiana 141 004, Punjab, India

<sup>3</sup>Department of Agronomy, Rajasthan Agricultural Research Institute (Sri Karan Narendra Agriculture University, Jobner), Durgapura, Jaipur 302 018, Rajasthan, India

\*Correspondence email - [pushpaagro95@gmail.com](mailto:pushpaagro95@gmail.com)

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## Abstract

India is the world's largest importer of edible oils, with an annual expenditure of approximately USD 10.5 billion, while ranking fourth in global vegetable oil production. Despite this production status, India remains heavily dependent on imports to meet its edible oil demands. Oilseed production in India is rainfed and has shown stagnation, with cultivation largely undertaken by marginal and smallholder farmers. Agricultural productivity can be enhanced using plant growth regulators (PGRs), which improve physiological responses to environmental stress. The present study investigates the effects of different PGRs-1 % potassium nitrate (KNO<sub>3</sub>), 200 ppm salicylic acid and 1 % urea on the growth, yield and economic returns of Indian mustard (*Brassica juncea* L.) under different agri-horticultural systems (AHS). The experiment was conducted at Indian Agricultural Research Institute, New Delhi, in the Rabi season of 2022–2023. It was laid out in a split-plot design with three main-plot treatments (Moringa based AHS, Phalasa based AHS and Karonda based AHS) and four sub-plot treatments (control, 1 % KNO<sub>3</sub>, 200 ppm salicylic acid and 1 % urea) with 3 replications. Results revealed that 1 % KNO<sub>3</sub> significantly improved dry matter accumulation, plant height and numbers of branches, while moringa-based AHS produced the highest yield (18.80 q/ha). Foliar application of 1 % KNO<sub>3</sub> resulted in the highest seed yield (18.86 q/ha) and stover yield (58.83 q/ha), outperforming the other treatments. The integration of PGR application with suitable AHS emerged as an effective strategy for enhancing the productivity and resource-use efficiency of Indian mustard, indicating its potential for improving crop yields in India's oilseed production systems.

**Keywords:** abiotic stress tolerance; foliar application; oilseed economics; rainfed ecosystems; resource-use efficiency

## Introduction

About 15 % of the world's imports of edible vegetable oil come from India (1). After USA, China and Brazil, India has the fourth-largest vegetable oil economy in the world, producing 37.7 million tonnes of oilseeds in 2021–2022 (2). Oilseed crops in India are predominantly cultivated under rainfed ecosystems, relying mainly on limited winter showers and conserved monsoonal rainfall. Domestic consumption of vegetable oils increased at a compound annual growth rate (CAGR) of 4.3 % over the previous 2 decades and it is anticipated that this trend would continue given the rising population, shifting demographics and rising per capita consumption because of higher GDP growth. India ranks third globally in terms of area and production of oilseeds, while ranking fifth with respect to yield per hectare (1). The country imports more than 50 % of its overall need for edible oil, thereby satisfying its need. Oilseed crops production is stagnant at roughly 1.0 t/ha due

to low levels of input consumption. Approximately 72 % of the total oilseed area is cultivated by marginal and small farmers under rainfed conditions. The duration and intensity of shading exert a detrimental effect on the growth of associated crops (3). To optimise resource utilisation, farmers adopt diversified combinations of annual and perennial crops, the agri-horticultural system is recognised for enhancing overall system productivity and resource-use efficiency (4).

The favourable microclimate created under agri-horticultural systems (AHS) supports the growth and development of crops such as Indian mustard. Crop performance is also impacted by the land arrangement for agri horticulture or in general (5). Crop growth and productivity will be examined in relation to the 3 mixtures of karonda, phalsa and moringa. Tree species composition affects soil biological properties, nutrient availability and soil moisture dynamics. Agri-horti systems are promising land-

use systems as they conserve soil and moisture, reduce soil erosion, sustain higher levels of productivity and income and generate additional employment opportunities, particularly during the off-season (6). Plant growth regulators (PGRs) are gaining popularity as of late because they enhance plants physiological responses to abiotic stresses, which in turn boosts and stabilises crop production. Plant growth regulators such as salicylic acid, thio-urea, potassium nitrate, salicylic acid and 1 % urea have all been reported to be beneficial for crop growth when used as PGRs (7–9). However, information on the integrated evaluation of these PGRs within different agri-horticultural systems for Indian mustard is limited. Therefore, the present study was undertaken to systematically evaluate the effects of different agri-horticultural systems and selected PGRs (KNO<sub>3</sub>, salicylic acid and urea), individually and in combination, on the growth, yield attributes, yield and biomass production of Indian mustard.

## Materials and Methods

The experiment was conducted at the Top Block Research Farm of the Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi, during the rabi season of 2022–2023. The experimental site is in a semi-arid climatic condition with 28° 40' N latitude, 77° 12' E longitude and at 229 m above the mean sea level. The field consist of an even topography with good drainage system.

The soil of the experimental site belongs to inceptisol soil order with sandy loam texture in the 0–30 cm topsoil layer. Composite soil sampling has done from top 0–15 cm soil layer before sowing by using the core sampler. Soil samples were analysed for physio chemical properties of soil and for major plant nutrients. The soil pH was recorded 7.8 with slightly alkaline condition and electrical conductivity (EC) was 0.32 ds/m. The total amount of rainfall received during crop growing season was 169.1 mm. During the crop growing season, maximum and minimum temperatures ranged from 34.6 °C to 4.3 °C. The maximum and minimum RH recorded during crop growing season was 87.5 % and 61.2 %. Meteorological data during the crop growing season (rabi 2022–2023) were obtained from the agrometeorological observatory located at the Indian Agricultural Research Institute (IARI), New Delhi, near the experimental site. Daily maximum and minimum air temperatures (°C) were recorded using maximum-

minimum thermometers housed in a Stevenson screen. Relative humidity (%) was measured using dry- and wet-bulb thermometers and expressed as daily maximum and minimum values. Rainfall (mm) was recorded using a standard rain gauge and daily rainfall amounts were summed to obtain seasonal totals. All meteorological observations were recorded following standard protocols of the India Meteorological Department (IMD). Seasonal mean values and cumulative rainfall were computed from daily records and are presented in Fig. 1.

The experiment was laid down in split plot design (SPD) with 3 main plot treatments comprises of moringa based AHS, Phalsa based AHS, karonda based AHS and 4 sub plot treatment comprises of PGRs i.e., control plot, 1 % KNO<sub>3</sub>, 200 ppm Salicylic acid and 1 % Urea and replicated thrice. The mustard variety used in the experiment was Pusa mustard 28 (PM 28). Seeds were sown at a seed rate of 5 kg/ha at a depth of 2–3 cm, maintaining a spacing of 30 × 10 cm. To maintain optimum amount of plant population gap filling and thinning is done at 15 days after sowing (DAS) in a cloudy day. Plant growth regulators i.e. 1 % KNO<sub>3</sub>, 200 ppm salicylic acid and 1 % Urea were applied in the form of foliar spray during 30 DAS, 60 DAS and 90 DAS separately in the individual plots. The concentrations of these agrochemicals (1 % KNO<sub>3</sub>, 200 ppm salicylic acid and 1 % urea) was adopted based on their proven efficacy in improving nutrient availability, photosynthetic efficiency, stress regulation without causing phytotoxic effects in Brassica and other oilseed crops. The spray timings at 30, 60 and 90 DAS corresponded to key phenological stages of Indian mustard vegetative growth, branching and flowering initiation and siliqua development, thereby ensuring effective regulation of physiological processes including canopy development, photosynthesis, nutrient translocation and assimilate partitioning.

Data analysis for each character was conducted using analysis of variance (ANOVA) and the significance of a split plot design was assessed using the 'F' test (13). Statistical analysis for the split-plot design was performed using the online Strengthening Statistical Computing for NARS (SSCNARS) portal. The treatment comparisons were made at a significance level of 5 % and critical difference (CD) and standard error of means (Sem±) were calculated for each character. Graphical representations were prepared where appropriate to illustrate treatment effects.

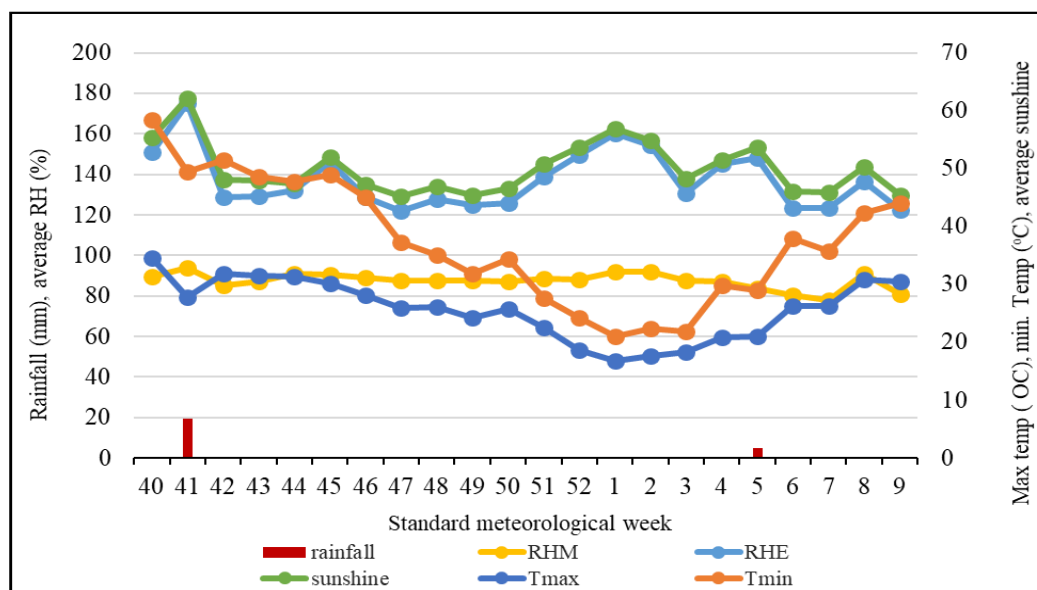


Fig 1. Graphical representation of weather parameters.

## Results

### Effect on growth parameters

The growth parameters viz. dry matter accumulation, plant height, number of primary, secondary and tertiary branches were analysed and depicted in Table 1. Data showed that the highest dry matter weight (43.87 g/plant and 78.31g /plant) was recorded with 1 % KNO<sub>3</sub> followed by 200 ppm SA (39.61 g/plant and 72.52 g/plant) at 90 DAS and after harvest, respectively. Enhancement in dry matter accumulation was 10.75 % and 22.88 % under 1% KNO<sub>3</sub> over 200 ppm SA and 1 % Urea at 90 DAS respectively. Among agri-horticultural systems, dry matter accumulation followed the order: Moringa-based AHS > Phalsa-based AHS > Karonda-based AHS. The maximum plant height of 130 cm at 60 DAS, 161.25 cm at 90 DAS and 173.58 cm at harvest was recorded under moringa based agri-horti system closely followed by Phalsa and karonda based AHS. Foliar application of 1 % KNO<sub>3</sub> resulted in a significant increase in plant height (127.66 cm at 60 DAS, 162.00 cm at 90 DAS and 171.33 cm at harvest) compared to the control. At harvest, plant height increased by 15.6 % under 1% KNO<sub>3</sub> and by 9.97 % under 200 ppm SA compared to the control. At harvest, the moringa-based system had more primary, secondary and tertiary branches per plant (7.75, 18.50 and 26.25), while the karonda-based system had the fewest (6.50, 16.08 and 22.66). The number of primary, secondary and tertiary branches per plant was higher with 1 % KNO<sub>3</sub> (8.33, 18.89 and 27.22, respectively) and it was comparable to the 200 ppm SA treatment in terms of secondary and tertiary branches, followed by 1 % Urea. No significant interaction effects were found between agri-horti systems and PGRs in influencing growth parameters.

### Effect on yield attributes

The yield attributes viz., numbers of silique per plant, seeds/silique, test weight (g) and main shoot length (cm) are depicted in Table 2. Moringa-based system achieved significantly higher numbers of silique per plant (394.25) compared to karonda (353.58) based system which remained 8 % and 11.5 % higher over Phalsa and Karonda based AHS. Among the PGRs, 1 % KNO<sub>3</sub> (416.33) remain statistically superior over 200 ppm SA (390.56) followed by 1 % Urea (353.89). Plots with 1 % KNO<sub>3</sub> treatment had 6.59 % higher numbers of silique per plant over 200 ppm SA and 17.6 % over 1% Urea treatment. The highest number of seed per silique was exhibited by moringa based (14.75), statistically comparable to phalsa-based system (14.42) followed by karonda (12.92). The maximum number of seed per silique observed with the 1 % KNO<sub>3</sub> application with 16.33 seed per silique, which was closely followed by 200 ppm salicylic acid (15.00).

**Table 1.** Effect of different plant growth regulators and agri-horticultural systems on the number of branches, dry matter accumulation and plant height of Indian mustard

Treatments	Dry matter accumulation (g/plant)			Number of Branches			Plant height (cm)		
	60 DAS	90 DAS	At Harvest	Primary branches	Secondary branches	Tertiary branches	60 DAS	90 DAS	At harvest
<b>Agri-horti system</b>									
<b>Moringa</b>	16.0	41.5	50.9	7.7	18.5	26.2	130.0	161.2	173.5
<b>Phalsa</b>	15.0	37.5	47.4	7.0	17.5	24.5	118.4	147.5	156.5
<b>Karonda</b>	13.9	33.9	37.5	6.5	16.0	22.6	112.5	139.6	147.5
<b>SEm±</b>	0.30	1.17	0.96	0.23	0.45	0.62	2.47	2.94	3.35
<b>LSD(p=0.05)</b>	1.19	4.59	3.77	0.92	1.80	2.53	9.98	11.88	13.53
<b>Plant growth regulators</b>									
<b>Control</b>	12.2	31.4	41.4	6.1	15.3	21.4	110.2	134.8	148.2
<b>1 % KNO<sub>3</sub></b>	17.3	43.8	51.3	8.3	18.8	27.2	127.6	162.0	171.3
<b>200 ppm Salicylic acid</b>	15.8	39.6	46.1	7.1	18.2	25.3	123.7	154.5	163.0
<b>1 % Urea</b>	14.5	35.7	42.3	6.7	17.0	23.8	119.5	146.5	154.3
<b>SEm±</b>	0.59	0.93	0.96	0.29	0.46	0.74	3.37	4.06	4.16
<b>LSD(p=0.05)</b>	1.77	2.77	2.87	0.87	1.37	2.23	10.10	12.18	12.47

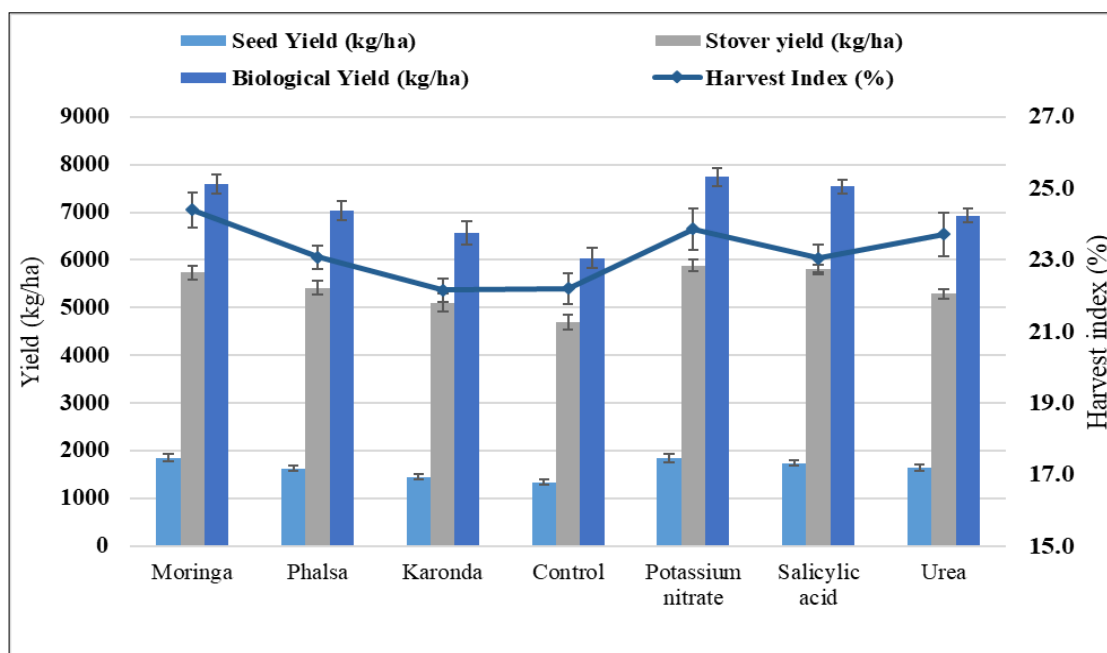
**Table 2.** Effect of different plant growth regulators and agri-horticultural systems on yield attributes viz., numbers of silique/plant, seeds/silique, test weight and main shoot length of Indian mustard

Treatments	Silique/Plant	Seeds/Silique	Test weight (g)	Main shoot length (cm)
<b>Agri-horti system</b>				
<b>Moringa</b>	394.2	14.7	4.6	70.7
<b>Phalsa</b>	364.9	14.4	4.4	64.2
<b>Karonda</b>	353.5	12.9	4.5	60.6
<b>SEm±</b>	6.18	0.27	0.08	1.81
<b>LSD(p=0.05)</b>	24.27	1.05	NS	7.32
<b>Plant growth regulators</b>				
<b>Control</b>	322.8	11.0	4.4	60.1
<b>1 % KNO<sub>3</sub></b>	416.3	16.3	4.7	68.0
<b>200 ppm Salicylic acid</b>	390.5	15.0	4.5	68.6
<b>1 % Urea</b>	353.8	13.7	4.4	64.1
<b>SEm±</b>	7.35	0.40	0.09	1.53
<b>LSD(p=0.05)</b>	21.85	1.18	NS	4.59

Application of 1 % KNO<sub>3</sub> enhanced the numbers of seeds/silique by 8.86 % and 18.5 % over 200 ppm salicylic acid and 1 % urea respectively. No of treatment exerted a statistically significant effect on 1000-seed weight; however, the highest 1000-seed weight was recorded with 1% KNO<sub>3</sub> (4.71 g), followed by 200 ppm salicylic acid (4.50 g). The Moringa-based AHS had highest 1000-seed weight value (4.62). Main shoot length was maximized with 200 ppm salicylic acid, while 1 % KNO<sub>3</sub> caused a significant increase while 1 % Urea produced a moderate enhancement. Among the agri-horticultural system, highest main shoot length of 70.7 cm was recorded under moringa based system, which was 10.12 % higher than phalsa (64.2 cm) and 16.67 % higher than karonda (60.6 cm).

### Effect on yield of Mustard

The moringa based treatment plots resulted in highest seed yield (18.80 q/ ha) followed by phalsa (16.26 q/ha) and Karonda based AHS (14.89 q/ ha). The Moringa based AHS settled 15.62 % and 26.25 % improvement in seed yield over phalsa and karonda based AHS, respectively. Among the PGRs, 1 % KNO<sub>3</sub> produced highest seed yield (18.86 q/ha) which was followed by 200 ppm salicylic acid (17.83 q/ha), 1 % urea treatment (16.46 q/ha) and control (13.44 q/ha). Treatment of 1 % KNO<sub>3</sub> produced 254 kg and 391 kg more seed yield per hectare than 200 ppm salicylic acid and 1 % urea treatment, respectively. The 1 % KNO<sub>3</sub> treatment recorded 5.77 %, 14.5 % and 40.32 % higher seed yield compared to 200 ppm salicylic acid, 1% urea and the control, respectively (Fig. 2).



**Fig. 2.** Graphical representation of yield parameters of Indian mustard.

The moringa based AHS (57.31 q/ha) displayed maximum stover yield, followed by phalsa based AHS (55.77 q/ha) and the lowest yield was recorded with karonda based AHS (51.08 q/ha). Plant growth regulators significantly enhanced the stover yield of mustard crop. The 1%  $\text{KNO}_3$  treatment recorded maximum stover yield (58.83 q/ha) which was statistically at par with 200 ppm salicylic acid (56.88 q/ha) followed by 1% urea (52.87 q/ha). The highest biological yield (76.11 q/ha) was recorded under the Moringa-based AHS and was statistically at par with the Phalsa-based (72.03 q/ha) and karonda-based (65.97 q ha<sup>-1</sup>) systems. Biological yield under moringa based AHS was 5.66% and 15.47% higher over Phalsa and Karonda based AHS, respectively. All the PGRs treatments remained statistically significant over control. The 1%  $\text{KNO}_3$  treatment recorded the highest biological yield (77.69 q ha<sup>-1</sup>), followed by 200 ppm salicylic acid (74.71 q ha<sup>-1</sup>), 1% urea (69.32 q ha<sup>-1</sup>) and the control (63.76 q ha<sup>-1</sup>). Biological yield under 1%  $\text{KNO}_3$  increased by 3.98%, 12.07% and 21.84% compared to 200 ppm salicylic acid, 1% urea and the control, respectively. There was no statistically significant interaction between agri-horti systems and PGRs with respect to yield.

## Discussion

### Effect on growth parameters

The AHS and PGRs significantly impacted the growth characteristics of mustard, including dry matter accumulation, plant height and the number of main, secondary and tertiary branches. Since soil moisture was sufficiently available in the moringa-based system up to the flowering stage, early-stage growth was not moisture-limited, resulting in minimal differences in dry matter accumulation among treatments during the initial growth period. Different AHS did not significantly affect plant height at 30 DAS. This was mainly due to slower growth at initial stages of the crop (10). However, at 60 DAS, 90 DAS and during harvest stage, different AHS influenced the plant height significantly, this was mainly due to grand growth phases of the crop which accelerated nutrient and water uptake from the soil and these physiological processes were directly influenced by growth regulators (11).

Enhanced plant height of Indian mustard due to application of different PGRs, plays a pivotal role in regulating numerous plant morpho-physiological and biochemical processes like seedling growth, stomatal regulation, photosynthetic rate, leaf senescence and flowering, enzyme activities in crops including edible oilseed crop plants (12, 10, 13). Plant response to ethylene increases because of salicylic acid's suppression of ethylene synthesis during drought stress, which may also affect proline metabolism, photosynthetic nitrogen uses efficiency and photosynthesis (14). When salicylic acid was applied topically, it might have a growth-stimulating effect on the accumulation of dry matter because of increased photosynthetic efficiency caused due to an increase in the amount of chlorophyll, the number of branches and leaf area index (15).

The number of primary, secondary and tertiary branches was significantly impacted by the agri-horti system. Due to more soil organic carbon, improved nutrient availability and the favourable microclimates under dense moringa foliage, the moringa-based system recorded the maximum number of primary, secondary and tertiary branches per plant, while karonda recorded the lowest (Table 1). In addition to being naturally high in macronutrients and micronutrients, moringa leaf also includes bioactive plant hormones, especially cytokinins like zeatin. Due to enhanced nutrient uptake and hormonal stimulation, these components promote axillary bud break, general shoot proliferation, branching and vegetative development (16). Potassium nitrate ( $\text{KNO}_3$ ) functions as a signalling molecule that controls axillary bud activation in addition to being an essential nutrient, it promotes branching. By interacting with hormonal mechanisms like auxin and strigolactones, nitrate availability significantly affects shoot branching and promotes more vigorous axillary bud growth (17).

Agri-horticulture systems and growth regulators had significant impact on growth and consequently the yield attributes of mustard (Table 2). The superior performance of mustard (e.g., silique number, seeds per silique, 1000 seed weight and main shoot length) under moringa-based system was recorded due to high quantity of leaf litter falls on soil which tend to improve soil fertility

and enhances crop growth due to high cytokinin levels (18). There was no discernible reaction to the use of PGRs in terms of 1000-seed weight across various agri-horticultural system treatments. The quantity of silique, seeds per silique and seed weight were significantly improved in  $KNO_3$  treatment plots. The beneficial effects of spraying this salt may be attributed to  $NO_3^-$ , which delays the synthesis of ascorbic acid and increases cytokine activity (19). On the other hand, salicylic acid regulates physiological processes including enhanced photosynthetic efficiency, metabolism and stress tolerance in mustard plant under elevated temperature, leading to higher vegetative growth and good yield performance (20, 21). Potassium nitrate and salicylic acid significantly increases shoot elongation compared to urea and control treatment by enhancing photosynthesis and nitrate reductase activity (22).

### Effect on seed and stover yield

Significant improvement was observed in seed and stover yield of mustard under various AHS (Fig 2) because residual and direct beneficial effect of tree species like moringa, phalsa and karonda. The biomass in terms of litterfall also added good quantity of the nutrients in the soil (4). Ultimately, there was more biomass buildup and improved canopy spread in terms of increased LAI since there was less competition between the trees and the field crops (23). The moringa-based AHS showed greater improvement in seed yield and superior growth parameters of field crops compared to phalsa and karonda based AHS. This was since moringa is multi purpose tree, it fixes substantial amount of atm -N into the soil (24, 25). Among the various PGR treatments, seed yield increased by 5.77 %, 14.5 % and 40.32 % with 1 %  $KNO_3$  treatments over 200 ppm salicylic acid, 1 % urea and control treatments, respectively. All PGR had a significant impact on yield components because salicylic acid and potassium operate as reactive oxygen species (ROS) scavengers, helping to maintain cellular water balance by minimising oxidative damage and promoting osmotic adjustment. They also promote nitrogen assimilation, resulting in higher proline and protein content. This increases the plant's ability to endure salt stress (26). As a result, these agrochemicals (Urea, salicylic acid and potassium nitrate) have the potential to increase water and agricultural productivity since

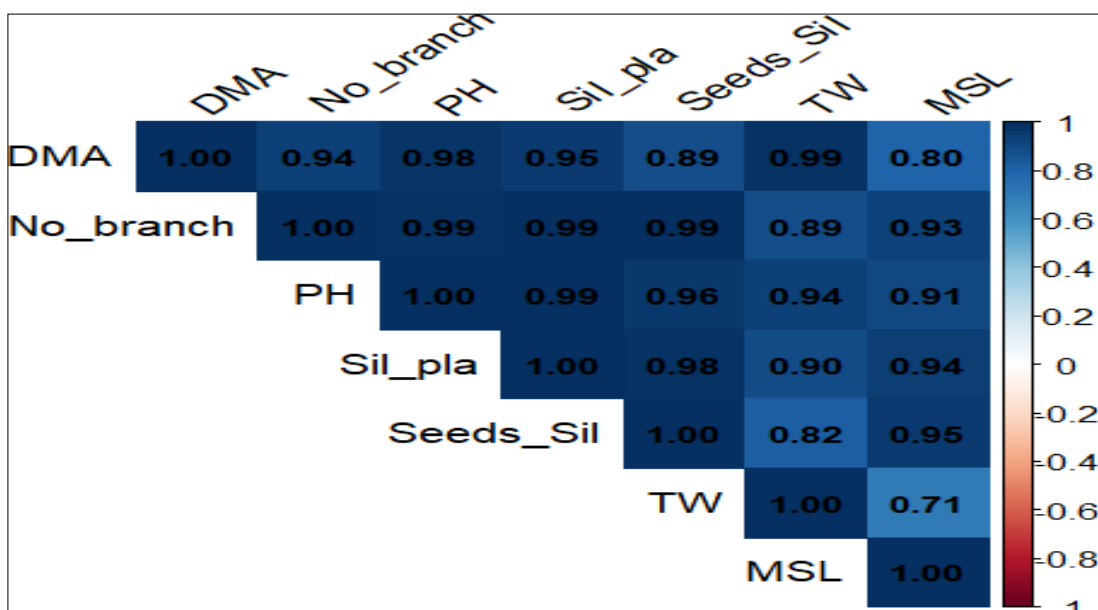
they efficiently promote crop assimilation partitioning and yield in water-stressed circumstances (27, 13).

Stover yield was also significantly increased with several AHS and PGRs treatments. However, the largest stover output was obtained under a moringa-based system, which contributes to soil fertility by increasing biomass decomposition in soil, even though its canopy spread was greater than Karonda and Phalsa, which cause shedding and impede proper plant growth (25, 28). Moringa tree canopy has an umbrella-shaped crown with bi-(tri-) pinnate leaves, but individual leaflets have a leaf area of one to two  $cm^2$ , but a larger canopy area (29). Plant growth regulator application considerably increases mustard stover output; however, 1 %  $KNO_3$  and 200 ppm salicylic acid produced significantly higher stover yield because nitrate salt has a beneficial influence on plant metabolism, promoting both seed and stover yield in oilseed *Brassica* crops (30). The beneficial effect of foliar-applied salicylic acid on dry matter accumulation may be attributed to enhanced photosynthetic efficiency through increased chlorophyll content, branching and leaf area index, resulting in higher dry matter production as well as increased seed and stover yields (15).

### Correlation studies

The correlogram (Fig. 3) illustrates the Pearson correlation coefficients among plant growth and yield parameters, namely dry matter accumulation (DMA), number of branches (No\_branch), plant height (PH), siliques per plant (Sil\_pla), seeds per silique (Seeds\_Sil), test weight (TW) and main shoot length (MSL). All traits exhibited positive and generally strong correlations, indicating a high degree of interdependence among growth and yield components.

Plant height (PH) showed very strong positive correlations with DMA ( $r = 0.98$ ), number of branches ( $r = 0.99$ ), siliques per plant ( $r = 0.99$ ), seeds per silique ( $r = 0.96$ ), test weight ( $r = 0.94$ ) and MSL ( $r = 0.91$ ). This suggests that taller plants possess greater photosynthetic capacity and biomass accumulation, which in turn supports enhanced branching and reproductive development, ultimately contributing to improved yield attributes. Taller plants generally possess greater leaf area and canopy architecture, which enhances light interception and photosynthetic efficiency, leading



**Fig. 3.** Correlogram showing relationships among plant growth and yield parameters.

DMA: Dry matter accumulation; No\_branch: Number of branches; PH: Plant Height; Sil\_pla: Siliques per plant; Seeds\_Sil: Seeds per silique; TW: Test weight; MSL: Main shoot length.

to higher biomass production and assimilate availability (31, 32).

The number of branches was also highly correlated with siliques per plant ( $r = 0.99$ ) and plant height ( $r = 0.99$ ), indicating that increased branching directly contributes to a higher number of reproductive sites. Its strong association with MSL ( $r = 0.93$ ) further suggests that vegetative vigour promotes both axial elongation and yield formation. Increased branching directly increases the number of reproductive sites, thereby contributing to higher silique production (33). The strong correlation between number of branches and MSL ( $r = 0.93$ ) further reflects the role of hormonal regulation and assimilate distribution in promoting both axial growth and reproductive sink development (34).

Siliques per plant exhibited an exceptionally strong correlation with seeds per silique ( $r = 0.98$ ) and DMA ( $r = 0.95$ ), underscoring its central role as a major yield determinant. This relationship reflects the cumulative effect of vegetative growth on sink development and seed formation. Adequate dry matter accumulation ensures sufficient assimilate supply during flowering and pod development, reducing floral abortion and improving seed set (35). Similar findings emphasizing siliques per plant as a key yield component in mustard have been documented (36).

Test weight exhibited strong positive correlations with DMA ( $r = 0.99$ ) and PH ( $r = 0.94$ ), suggesting that improved source strength and efficient assimilate translocation enhance seed filling and final seed mass (37). The comparatively lower correlation between TW and MSL ( $r = 0.71$ ) indicates that seed weight is influenced more by physiological efficiency and carbohydrate partitioning during the seed-filling stage than by shoot elongation alone. However, the lowest correlation, though still positive, was observed between TW and MSL ( $r = 0.71$ ), suggesting that seed weight is more influenced by assimilate availability and physiological efficiency than by shoot length alone.

Overall, the correlogram reveals that growth traits such as plant height, branching and dry matter accumulation act synergistically to enhance yield components, including siliques per plant, seed number and seed weight. The strong interrelationships highlight the coordinated response of growth and yield traits, likely mediated by improved source–sink balance under the influence of PGRs.

## Conclusion

The moringa-based system consistently improved growth parameters, yield attributes and productivity by creating favorable microclimatic conditions and enhancing nutrient availability. Foliar application of 1%  $\text{KNO}_3$  was most effective in increasing dry matter accumulation, plant height, branching and yield components, leading to the highest seed and stover yields. These agrochemicals can be potentially used to increase water and crop productivity, improve assimilate partitioning and yield under irrigation deficit conditions and can be recommended for enhancing mustard productivity under rainfed and semi-arid regions.

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technicians and batch mates for their valuable assistance during the experimental setup and data collection.

## Authors' contributions

SPB and SSR contributed to the conceptualization of the study. SSR and KS developed the methodology. Investigation and data curation were carried out by SPB. The original draft of the manuscript was written by PP. Review and editing of the manuscript were performed by PP and R. Supervision of the work was provided by DM and PD. 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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