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Effect of the System Intensification on Growth and Yield of Mustard Varieties

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The gradual changes in season and temperature are making mustard growing more challenging. The method of planting is the main factor that determines the optimal growth and development of mustard. The study was conducted at Regional Research Station (OAZ), UBKV, Majhian during two *rabi* season (2021-22 and 2022-23), on growth and production of three mustard hybrid varieties viz. Pioneer 45S46, Kesari 5100, and Kesari Gold, using three types of planting techniques: S_1: broadcasting, S_2: line sowing, and S_3: system of mustard intensification. The experiment was laid out in a split plot design replicated thrice. The results showed that system of mustard intensification was significantly higher responses in seedling growth and yield characteristics than the direct

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sowing of broadcasting and line sowing methods. The variety V_3 was found most superior in terms yield traits. The V_3S_3 treatment was found most significant interaction effect which was recorded highest seed yield (1875.26 kg ha^{-1}), dry matter content (115.0 g), leaf area index (4.46), and crop growth rate (6.43 g/m2/day). The maximum production efficiency was found in V_3S_3 (18.16 kg ha^{-1} day^{-1}) in 2022, whereas in 2023 it was maximum in V_1S_3 (19.76 kg ha^{-1} day^{-1}).The mustard intensification system is a potential agricultural invention that aids in production, reduces import demands, and encourages efficient and sustainable mustard farming.

Keywords: Hybrid; seedling; traits; sustainable.

1. INTRODUCTION

The Brassica species, commonly known as rapeseed-mustard, is the third most important oilseed crop cultivated worldwide after soybean and palm, and is one of the most commercially significant agricultural commodities. India produces around 11% of the world's rapeseed mustard, making it the third-largest producer after China and Canada. It is the second most important edible oilseed in India after groundnut, with an area of 8.06 million hectares and a productivity of 1458 kg ha^{-1} in 2021–2022, accounting for 27.8% of the country's oilseed economy. In most states throughout the country, mustard is grown. Mustard is grown widely in UP, Gujrat, and Rajastan, but in West Bengal under irrigated conditions (Ray et al*.,* 2015), yielding approximately 0.76 million tons with a productivity of 1250 kg ha^{-1} year-round (GoI, 2022). Over the past two decades, it has gained popularity in the North Bengal regions (Pandit et al*,* 2016). Nevertheless, the majority of farmers still use fairly simple management techniques by direct sowing to produce mustard as a paira crop in the rice field by disseminating it with residual soil moisture. Consequently, when compared to a single crop, this crop's growth and production performance are consistently inferior (Banerjee et al*.,* 2018). Further, the first two weeks of October is the best time of year to plant the oilseed Brassica in India. However, because *kharif* rice harvesting is delayed, these crops are not planted until November or the first week of December. As a result of delayed seeding, mustard productivity eventually declines.

System intensification is one of the strategies that, by managing natural resources properly and using a variety of crops in different agro-ecologies, increases agricultural productivity while conserving resources and promoting sustainability and climate resilience(Adhikari et al*.,* 2018; Rathore et al*.,* 2020). A variety of crops, such as rice, wheat, sugarcane, and mustard, can benefit from the use of agricultural intensification techniques. A novel strategy for increasing oilseed production above the traditional planting system, the system of mustard intensification (SMI) raises mustard productivity through adjustments to soil, plant, moisture, and nutrient management techniques. This method of increasing seedling growth and yield through root intensification through transplanting mustard seedlings is already being used in some irrigated rapeseed-mustard-growing regions of India (Chaudhary et al., 2016; Pandit et al., 2022). This system of intensification techniques for mustard is improving the efficiency of input utilization, improving yield, and resolving the issue of delayed sowing. By altering management strategies, it also enhances root growth, improving soil function and protects the crop from biotic and abiotic stress (Adhikari et al*.,* 2018). Compared to other methods like broadcasting and line sowing, SMI transplants mustard seedlings with a wide spacing, providing for proper plant density and root system development from early crop growth. Plant-microorganism interactions were found to be greater in terms of water and nutrient uptake when there was a large root system presents (Anas et al*.,* 2011; Thakur et al., 2013). But there is still a lack of proper methodology and effective cultivation practices through the system of mustard intensification. In order to compare the growth, yield, and physiological characteristics of three distinct mustard varieties, as well as the effects of their interactions, the current study was conducted using three different methodologies: broadcasting, line sowing, and SMI technology.

2. MATERIALS AND METHODS

2.1 Experimental Location

The experiment was conducted at the Regional Research Station (OAZ), Uttar Banga Krishi Viswavidyalaya, Majhian, Dakshin Dinajpur, W.B., India, which is located at latitude 26019'86''N and longitude 89023'53''E. Its average elevation is 43 meters above mean sea level. The soil of the study area was clay loam with acidic in nature.

Table 1. Cultivation management practices of different planting methods

Sl No.	Particulars	Treatment details		
		Broadcasting method (S_1)	**Line sowing method (S_2)**	**System of mustard Intensification (S_3)**
1.	Seed rate	6 kg/ha	4 kg/ha	400 g/ha
2.	Nursery management	Not required	Not required	Small miropot (2 cm × 2.5 cm) required and placing one seed in each
3.	Methods of sowing	Broadcasting	Line sowing	Transplanting after two week
4.	Spacing	Broad casting No proper spacing	Rectangular crop geometry 30 cm x 30 cm	Square crop geometry (45 cm x 45 cm)
5.	Date of sowing/ Transplanting	Sowing: 22nd November 2021 and 2022	Sowing: 22nd November 2021 and 2021	Sowing: 22nd November 2021 and 2022 Transplanting: 5th November 2021 and 2022
6.	Irrigation	2-3 required. At the time of branching, flowering, silique formation, and seed development stages	3-4 required. At the time of branching, flowering, silique formation, and seed development stages	4-5 required. Shallow irrigation at 15, 30, 45, 60, and 80 DAT
7.	Weed management	Herbicide approach Pendimethalin@1.5ml/lit	Pendimethalin @1.5ml/lit	Mechanical weeding
8.	Nutrient management	Primarily fertilizer-based, all fertilizers are applied at the time of sowing, except for nitrogen NPK @ 60:40:40 kg ha^{-1}	NPK @ 60:40:40 kg ha^{-1}	NPK @ 60:40:40 kg ha^{-1} Applied 50% N before planting. 1/3 dose of N15-20 DAT 45 DAT 1/3 dose of N
9.	Pest management	Three spray required ofImidacloprid@2.5ml/lit	Three spray required of Imidacloprid @2.5ml/lit	Two spray required of Imidacloprid @2.5ml/lit
10.	Date of harvesting	25th February 2023 and 2024	23rd February 2023 and 2024	22nd February 2023 and 2024

2.2 Experimental Materials and Sowing Methodology

The experiment was laid down in a split plot design with three replications. The varieties of mustard were used a main factor namely. Pioneer 45546 (V_1), Kesari 5100 (V_2), and Kesari Gold (V_3) were used for the study. These varieties were collected from the Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal, India. Three different sowing methodology was implemented such as S_1: Broadcasting direct sowing (Conventional method); S_2: Line sowing (direct); and S_3: System of Mustard Intensification (SMI) (transplanting method) were followed each of these varieties.

2.3 Management of Different Planting Methods

In the system of mustard intensification (SMI), 12 days old seedling was prepared in small micro pots (2 cm×2.5 cm size). Cultural management, fertilizer application, intercultural operation, irrigation, and plant protection measures for all the three methods are presented in Table 1. A preliminary assessment of soil fertility was conducted and is shown in Table 2.

2.4 Seedling Parameter

After three week of planting in different system among the variety, the seedling growth study was determined. Different seedling parameter such as root length (cm), shoot length (cm), number of leaves, fresh root weight (gm), fresh shoot weight(gm), dry root weight (gm), dry shoot weight (gm) were measured each of the treatments.

2.5 Observation of Growth and Yield Parameter of Mustard

Several yield-attributing characteristics, including plant height (cm), number of primary branches, number of secondary branches, number of leaves plant^{-1}, number of plant per m^2, number of siliqua plants^{-1}, test weight (gm), and seed yield kg ha^{-1}were estimated throughout the growth period. The total chlorophyll content (mg/100g fresh weight) was measured according toprotocol of Davies (1976). The dry matter content (gm) was calculated as the dry weights of the plant components at 90 DAS. Five plants of each variety were picked at their individual growing periods. The leaf area index (LAI), and crop growth rate (CGR) was measured during maturity of the plants. The harvest index (HI) was estimated after harvesting of the crop using following formula:

Harvest index (%) = Grain yield / Biological yield × 100.

The production efficiency (kg ha^{-1} day^{-1}) of different treatments were calculated using following formulas:

Production Efficiency (PE) = Seed yields (kg ha^{-1})/Crop duration (days)

Table 2. Physico-chemical properties of the experimental site

Particulars	**Years**	
	2021-22	**2022-23**
a. Mechanical composition		
Sand	20.46	20.10
Silt	27.23	27.49
Clay	52.31	52.41
Textural class	Clay loam soil	
Bulk Density (Mg m^{-3})	1.29	1.31
Particle Density (Mg cm^{-3})	2.67	2.68
b. Chemical properties		
Organic carbon (%)	0.48	0.50
pH (1:2.5Soil: water suspension)	5.25	5.27
Electrical conductivity (mmhos cm^{-1})	5.6	5.5
Available Nitrogen (kg ha^{-1})	265	262
Available phosphorus (kg ha^{-1})	42	39
Available potassium (kg ha^{-1})	310	316
Available S (µg g^{-1} in soil)	14	13
Available B (µg g^{-1} in soil)	0.32	0.34

2.6 Statistical Design and Analysis

A split plot design was used for the experiment, and each treatment was replicated three times. Using two-way ANOVA, the significance and interactions between treatments were assessed using SPSS 16.0 software. Differences between treatment means were compared using Duncan test at a 5% probability level (p = 0.05). The correlation and biplot analysis was performed using R statistical software.

3. RESULTS AND DISCUSSION

3.1 Seedling Growth Determination

The growth characteristics of the seedlings were significantly ($p < 0.05$) impacted by the various varieties, seeding techniques, and their combinations (Fig. 1). The different sowing methods had a substantial impact on the growth of mustard seedlings at three week age (Fig. 2). Among the variety V_3 was found most effective for seedling growth of shoot length, number of leaves, fresh shoot weight, fresh shoot weight, dry root weight and dry shoot weight. V_1 was found promising for root length. The most effective treatments, considering SMI, had the highest root length, shoot length, number of leaves, fresh shoot weight, fresh shoot weight, dry root weight and dry shoot weight with an increase of 144.63%, 70.35%, 65.14%, 95.93%, 131.99%, 1500%, and 99.26% over the conventional broadcasting method and 110.35%, 27.81%, 31.58%, 423.91%, 115.77%, 814.29% and 61.08% over the line sowing methods, respectively. The seedling characteristics interaction effects of between variety and sowing methods also found significant variable each other. Among all the treatments V_3S_3 was found most superior for seedling characteristics of shoot length, number of leaves, fresh shoot weight, fresh shoot weight, dry root weight and dry shoot weight (Fig. 1).

3.2 Interaction Effects of Yield Component Traits

Three varieties of different genetic backgrounds were used for screening under several of sowing methods by evaluating the morphological characters. Growth and various yield attributes of mustard were significantly influenced by different sowing dates and varieties (Table 2). The results of the analysis of variance showed a high degree of variability with significant differences among the three varieties and the treatments (sowing methods) combination for all the characters studied. Mean performance genotypes and the treatments are represented in Table 3. The maximum root length, plant height, number of primary branch, number of secondary branch, pod number per plant, number of siliquaplant^{-1}, seed yield, test weight, were recorded in SMI, and were statistically superior to the conventional method and line sowing. The early flowering was also observed in SMI, whereas delay flowering and maximum number of plant leaf per meter square was found in conventional broadcasting method followed by line sowing. The increase in root length, plant height, number of primary branch, number of secondary branch, number of siliqua plant^{-1}, number of leaves plant^{-1}, seed yield, test weight, and harvest index in the SMI method was 54.34%, 15.34%, 351.14%, 418.44%, 118.41%, 120.78%, 16.03%, 32.18%, and 13.94% over the conventional and 37.46%, 11.26%, 203.65%, 278.12%, 83.85%, 14.36%,24.46%,and 20.78% over the line sowing method, respectively.

The results revealed that the variety V_1 significantly superior over others for plant height, early flowering and test weight. The number of primary branch, number of secondary branch, pod number per plant were found most superior in V_2 and whereas, number of siliqua plant^{-1}, number of plant leaf per meter square, and seed yield were maximum in V_3 (Table 3).

The SMI approaches showed a considerable improvement in growth, yield components, and yield when variety and sowing methods were combined. The maximum, number of siliqua plant^{-1}, number of plant leaf per meter square, and seed yield were maximum were significantly greater in the V_3S_3treatment combination than in the other treatments. The second-highest increases in plant growth, yield variables and yield were obtained with the V_2S_3 combination. Conversely, all the corresponding values were significantly minimal for the V_1S_1 combination (Table 3). Contrary, harvest index is estimated with seed and biological yield and presented in the Table 3. It was found significantly higher in V_2 and least value of harvest index was observed in V3. SMI planting method was resulted in significantly higher harvest index than the harvest index in other direct seeding. However, interestingly V_2S_3 was observed with maximum harvest index (13.25%) whereas minimum value recoded in V_3S_2.

Table 3. Effect of different variety and sowing methods on growth, and yield traits of mustard (Pooled data)

Treatments	RL	PH	NPB	NSB	FF	NSPP	NLPP	NPPM	SY	TW	HI
V_1	23.35a	156.28a	7.51c	11.17b	38.67a	211.35b	27.39b	43.67b	1618.79b	5.34a	13.70a
V_2	20.77b	143.92c	8.91a	11.83a	40.67b	118.99c	24.81c	41.33b	1346.71c	4.38c	13.74a
V_3	23.08a	150.63b	8.08b	11.00c	42.33c	418.86a	30.33a	53.00a	1721.69a	5.00b	12.75b
SE (m)±	0.25	0.83	0.05	0.05	0.41	2.77	0.37	2.68	15.40	0.05	0.19
LSD ($P < 0.05$)	1.00	3.36	0.22	0.20	1.86	11.18	1.50	9.55	62.09	0.20	0.53
S_1	18.33c	141.32c	3.50c	4.50c	43.67a	173.36c	18.72c	66.33a	1476.32b	4.35c	11.48b
S_2	20.58b	146.51b	5.20b	6.17b	41.67b	197.20b	22.48b	59.67a	1497.88b	4.62b	10.83c
S_3	28.29a	163.00a	15.79a	23.33a	36.33c	378.64a	41.33a	12.00b	1713.00a	5.75a	13.08a
SE (m)±	0.20	1.33	0.06	0.07	0.52	5.45	0.28	7.95	12.73	0.08	0.21
LSD ($P < 0.05$)	0.62	4.17	0.21	0.22	2.03	18.29	0.89	24.77	39.67	0.24	0.56
Interaction (V×S)											
V_1S_1	19.26d	145.32cd	4.00f	4.50g	42.00b	132.58e	18.45g	62.00c	1405.19c	4.27e	11.06e
V_1S_2	21.60c	149.98cd	5.50e	6.50e	40.00b	156.23d	22.48e	57.00d	1611.70b	5.17c	11.16e
V_1S_3	29.20a	173.54a	13.03c	22.50b	34.00e	345.25b	41.25b	12.00g	1839.49a	6.59a	13.01b
V_2S_1	16.88e	138.90d	2.50g	3.50h	44.00a	96.25f	16.45h	59.00d	1385.59d	4.64d	11.47d
V_2S_2	18.98d	141.83d	4.00f	4.50g	41.00b	110.25f	20.45ef	53.00f	1230.29e	3.92f	11.13e
V_2S_3	26.46b	151.04c	20.22a	27.50a	37.00d	150.48d	37.52c	12.00g	1424.24c	4.59de	13.25a
V_3S_1	18.86d	139.74d	4.00f	5.50f	45.00a	291.25d	21.25e	78.00a	1638.17b	4.15e	11.90c
V_3S_2	21.16c	147.72cd	6.11d	7.50d	44.00a	325.12c	24.52d	69.00b	1651.65b	4.78d	10.19f
V_3S_3	29.22a	164.43b	14.13b	20.00c	38.00	640.20a	45.23a	12.00g	1875.26a	6.06b	12.96b
SE (m)±	0.27	2.13	0.11	0.11	0.43	5.53	0.53	0.84	23.30	0.07	0.18
LSD ($P < 0.05$)	1.11	6.45	0.34	0.34	1.58	16.73	1.62	2.56	70.45	0.22	0.51

RL= Root length (cm), PH= Plant height (cm), NPB= Number of primary branch, NSB= Number of secondary branch, FF= fifty percent flowering, NSPP= Number of siliqua plant^{-1}, NLPP= Number of leaves plant^{-1}, NPPM= Number of plants per m^2, SY= Seed yield, TW= Test weight (gm),HI= Harvest index (%), V_1=45S46, V_2=Kesari 5100, V_3=Kesari Gold, S_1=Broadcasting method, S_2=Line sowing, S_3=System of Mustard Intensification (SMI). LSD=Least significance difference at 5% levelDifferent letters within the same column indicate significant differences at $P < 0.05$ according to DMRT test

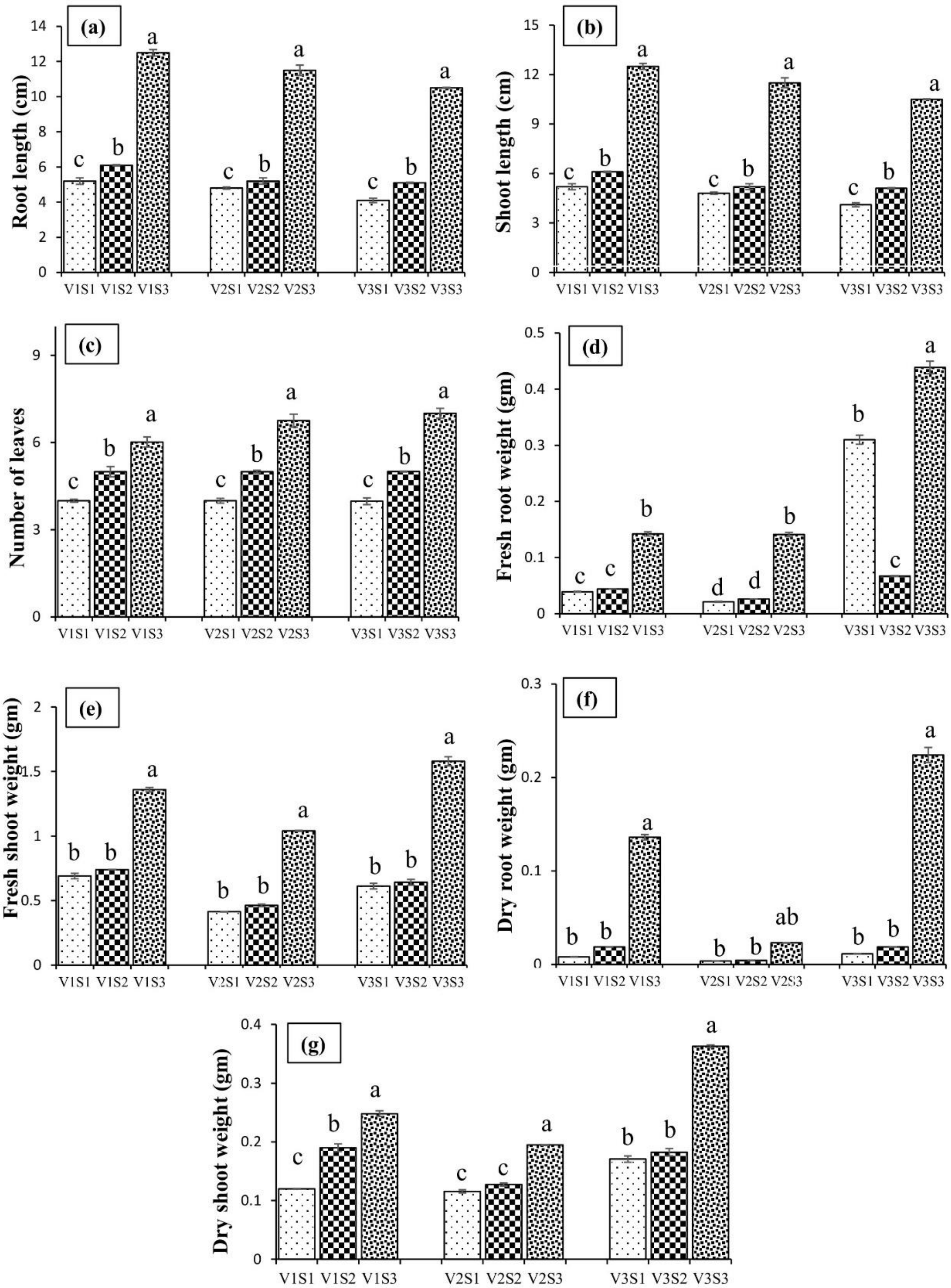

Fig. 1. Effect of different variety and planting methods on seedling growth mustard. (a)Root length (cm), (b)Shoot length (cm), (c)Number of leaves, (d)Fresh root weight (gm), Fresh shoot weight (gm), (e)Dry root weight (gm), (f)Dry shoot weight (gm). Means sharing different letters are significantly (p ≤ 0.05) different from each other

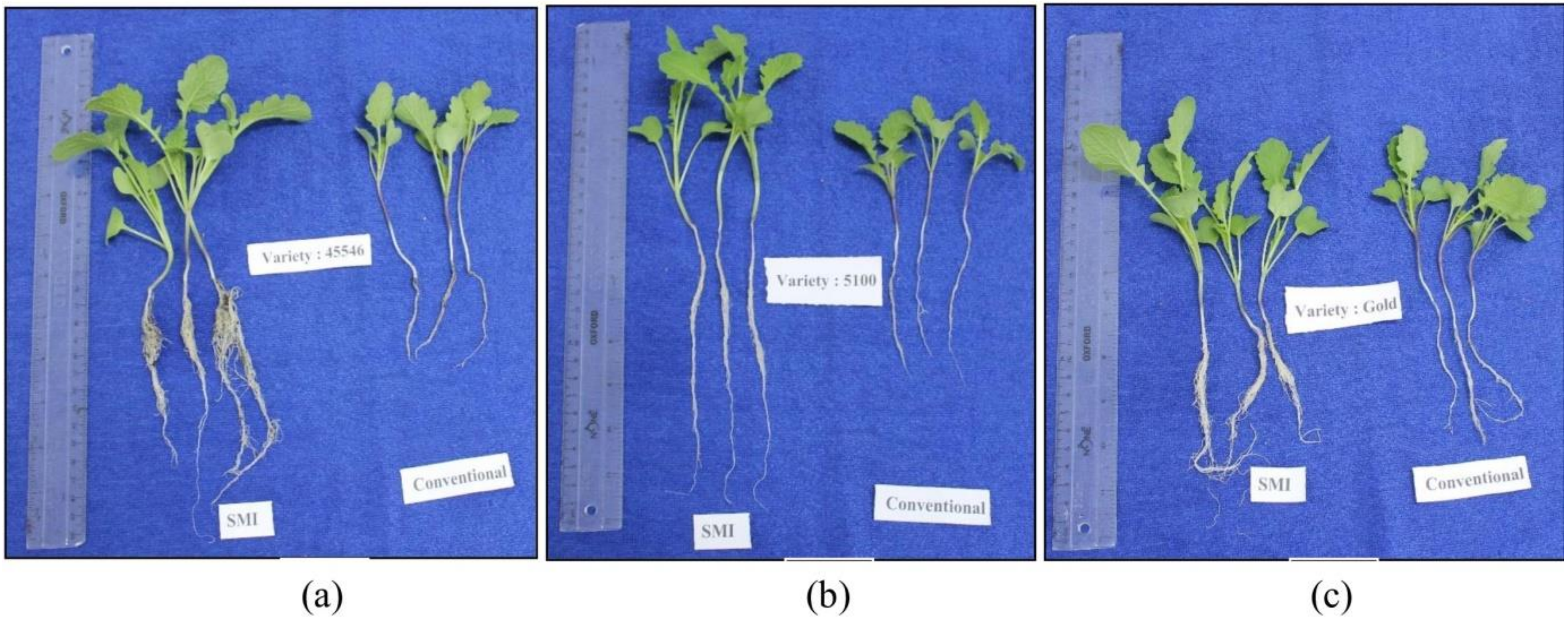

Fig. 2. Comparison of seedling characteristics of Conventional and SMI methods in different varieties of mustard. (a) Variety 45S46, (b) Kesari 5100, (c) Kesari Gold

3.3 Chlorophyll Content, Dry Matter Accumulation, Leaf Area Index and Crop Growth Rate

The total chlorophyll content among the varieties significantly varied (Table 4). Maximum chlorophyll content among was found in V_1 followed by V_3. Significantly higher chlorophyll content was recorded in SMI with 9.49% and 4.58% increase over direct and line sowing methods, respectively. The interaction effect was maximum found in V_1S_3 followed by V_3S_3 and least value in V_2S_1. Dry matter accumulation (DMA) at maturity stage of mustard growth is presented in Table 4. Data showed that the dry matter accumulation at maturity growth stage of mustard significantly affected by combined effect of planting methods. The highest DMA was recorded in V_3S_3 (115.0 g), whereas, lowest in V_2S_1 (15.69 g). DMA per plant was significantly influenced by mustard planting methods. However, DMA in direct sowing broad casting and line sowing method was found statistically at par each other. LAI was found significant even at maturity stage, higher LAI was recorded in transplanted V_3at all the planting methods (Table 4). The SMI technique of wider scale resulted in higher LAI, which increases 63.56% and 40.32% compared conventional and line sowing methods (Table 4). The crop growth rate was estimated during maturity stage and found significantly higher in V_3 (4.64) and least value of was observed in V_2 (4.54). SMI planting method was resulted in significantly crop growth rate. The maximum treatment interaction effect of crop growth rate was obtained from V_3S_3 whereas minimum value recoded in V_3S_1.

3.4 Correlation Analysis and Principle Component Analysis of Growth and Yield Component Traits

The correlation coefficient analysis of mustard varieties with different sowing methods resulted the traits particularly root length, plant height, number of leaf plant^{-1}, number of siliqua plant^{-1}, test weight and total chlorophyll content were found significant and positive associated with seed yield (Fig. 3). Root length was found positive significant association with all the characteristics except number of plant per m^2, and fifty percent flowering. On the other

Table 4. Effect of different variety and sowing methods on chlorophyll content and physiological attributes of mustard (Pooled data)

Treatments	TCC	DMC	LAI	CGR
V_1	72.47a	50.31b	3.24b	4.60b
V_2	68.74b	39.21c	3.38a	4.58b
V_3	71.62a	52.83a	3.32ab	4.64a
SE (m)±	0.42	0.78	0.02	0.001
LSD (P < 0.05)	1.44	2.16	0.08	0.04
S_1	67.74c	17.72c	2.62c	3.55c
S_2	70.92b	21.29b	3.05b	4.09b
S_3	74.17a	103.33a	4.24a	6.19a
SE (m)±	0.52	1.19	0.08	0.12
LSD (P < 0.05)	2.62	4.26	0.18	0.31
Interaction (V×S)				
V_1S_1	69.71c	18.23e	2.46e	3.56d
V_1S_2	71.92b	22.70de	3.11c	4.13c
V_1S_3	75.77a	110.00b	4.15b	6.12b
V_2S_1	65.03d	15.69e	2.76d	3.62d
V_2S_2	68.69c	16.93e	2.96cd	4.11c
V_2S_3	72.50b	85.00c	4.11b	6.01b
V_3S_1	68.47c	19.25e	2.63d	3.48d
V_3S_2	72.15b	24.25d	3.08c	4.02c
V_3S_3	74.24a	115.00a	4.46a	6.43a
SE (m)±	0.49	1.1	0.04	0.07
LSD (P < 0.05)	2.03	3.46	0.13	0.25

TCC= Total chlorophyll content (mg/100g), DMC=Dry matter content (gm), LAI= Leaf area index, CGR= Crop growth rate (g/m2/day), V_1=45S46, V_2= Kesari 5100, V_3= Kesari Gold, S_1= Broadcasting method, S_2= Line sowing, S_3= System of Mustard Intensification (SMI). LSD=Least significance difference at 5% level Different letters within the same column indicate significant differences at P < 0.05 according to DMRT test

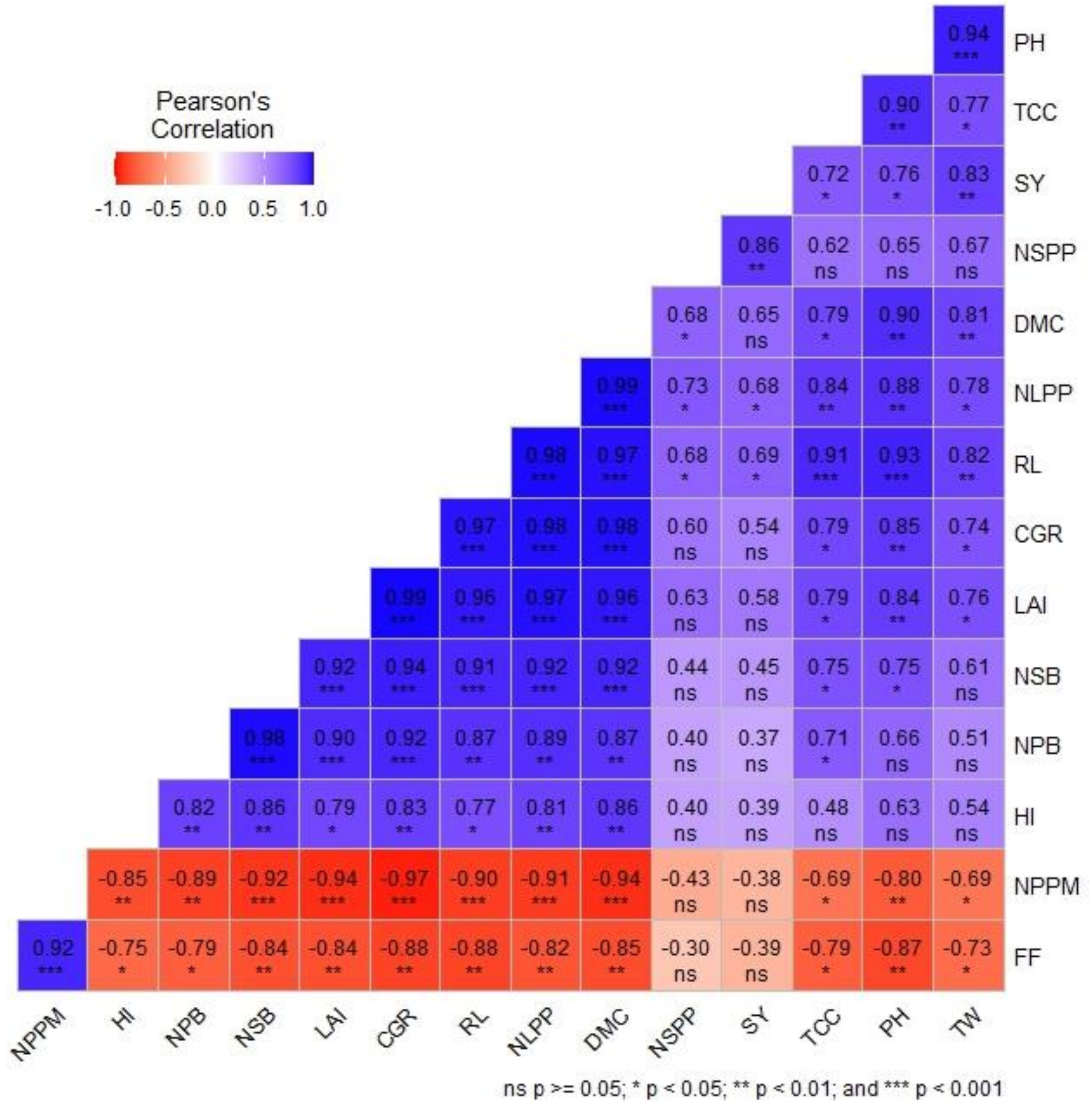

Fig. 3. Correlation of growth and yield traits of mustard

*RL=root length (cm), PH =plant height (cm), NPB=number of primary branches, NSB=number of secondary branches, NLPP=Number of leaf per plant, NPPM= number of plant per m^2, NSPP=number of siliqua plants^{-1}, TW=test weight (gm), SY=seed yield kg ha^{-1},TCC= total chlorophyll content (mg/100g fresh weight), DMC= dry matter content (gm), LAI=leaf area index (LAI), CGR=crop growth rate (CGR),HI= The harvest index (%), *Significant (p ≤ 0.05), ** Highly significant (p ≤ 0.01), *** Highly significant (p ≤ 0.001), ns= non-significant*

hand plant height also found significantly and positively correlated with seed yield, number of siliqua plant^{-1}, test weight, total chlorophyll content, dry matter content, root length, number of leaf plant^{-1}, leaf area index, crop growth rate, and number of secondary branch. Plant height significant negative association was observed for number of leaf plant^{-1} and fifty percent flowering. Dry matter content was found significant association for all the characteristics except seed yield. The leaf area index and crop growth rate was found significant positive association with root length, plant height, number of leaf plant^{-1}, number of primary branch, number of secondary branch, number of siliqua plant^{-1}, test weight, harvest index, dry matter content and total chlorophyll content (Fig. 3).

The PCA analysis detected the parameters that were most responsible for growth and seed yield characteristics of mustard treatment combination. The PCA indicated that the first two principal components explained 90.70% of the variance in all traits tested (Fig. 4). In the first principal component, 79.8% of the contribution was mainly from root length, plant height, number of leaf plant^{-1}, number of primary branch, number of secondary branch, number of siliqua plant^{-1}, test weight, harvest index, seed yield, number of siliqua plant^{-1}, leaf area index, crop growth rate, dry matter content and total chlorophyll content. The first PCA indicated maximum characters contributed from V_3S_3 followed by V_2S_3 and V_1S_3 treatments. In the second principal component, accounted 10.9% contribution from the number of plant per m^2, and fifty percent flowering of V_3S_1, V_3S_2 and V_1S_2 treatments.

3.5 Production Efficiency of Mustard

The production efficacy of mustard varieties under different planting methods in 2022 and 2023 is presented in Fig. 5. The maximum production efficiency was found in V_3S_3 (18.16 kg ha^{-1} day^{-1}) in 2022, whereas in 2023 it was maximum in V_1S_3 (19.76 kg ha^{-1} day^{-1}).The highest production efficiency was obtained by V_1S_3, V_3S_3, andV_3S_3were significantly higher by 61.21% and 31.70%, 61.51% and 13.10%, 36.68% and 13.12% over broadcasting and 30.14% and 16.03%, 35.99% and 14.81%, 28.28% and 14.01% over line sowing in both the year of 2022 and 2023, respectively (Fig. 5).

Effective sowing techniques and seedling quality, which are controlled by seeding density in the field, have a significant impact on mustard productivity. The methods of planting had a substantial impact on the growth of the mustard seedlings. When compared to conventional and line sowing methods, the SMI approach showed better root growth and higher seedling height.

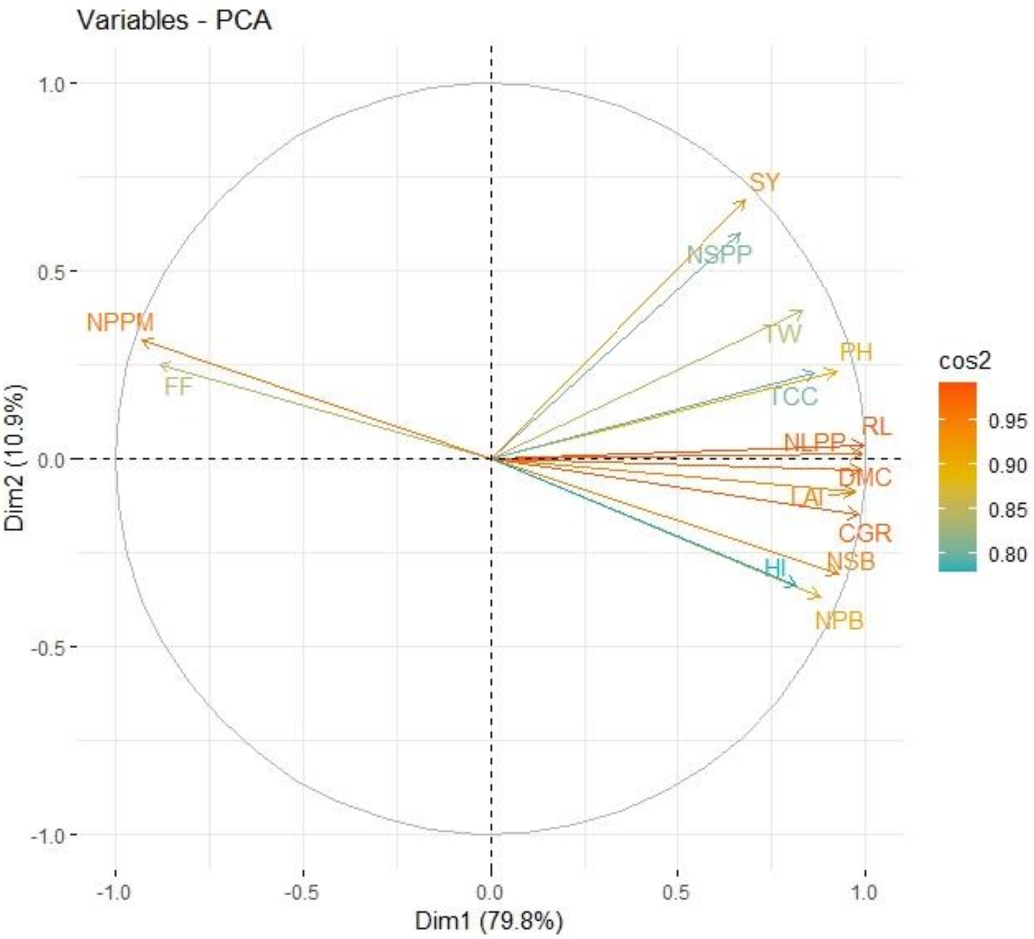

Fig. 4. Principle component analysis (PCA) of growth and yield traits of mustard

RL=root length (cm), PH =plant height (cm), NPB=number of primary branches, NSB=number of secondary branches, NLPP=Number of leaf per plant, NPPM= number of plant per m^2, NSPP=number of siliqua plants^{-1}, TW=test weight (gm), SY=seed yield kg ha^{-1},TCC= total chlorophyll content (mg/100g fresh weight), DMC= dry matter content (gm), LAI=leaf area index (LAI), CGR=crop growth rate (CGR), HI= The harvest index (%)

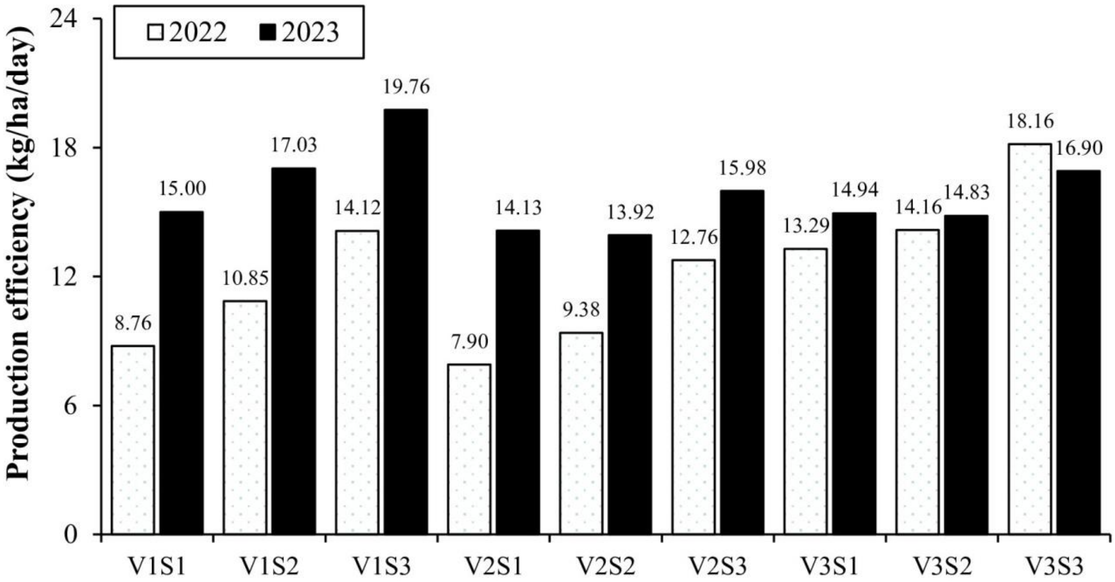

Fig. 5. Production efficiency (kg ha^{-1} day^{-1}) of different treatment combination of mustard for 2022 and 2023

This is because low-density plants are given the proper quantity of light, nutrients, and space to flourish, it was observed. Because of the impact of spacing in the SMI method, a significant amount of variation was seen in the case of root length per seedling of mustard. The method of planting of SMI and comparison with the conventional methods for root growth and yield is shown in Fig. 6a-g. In this instance, increased plant density might have led to less light interception per plant, which might have decreased biomass accumulation and photosynthesis per plant. There will also be more competition for water and minerals between the seedlings' roots when they are spaced closer together. Under SMI, the plants are able to invest in robust root growth in addition to shoot growth. Therefore, at a larger plant density in the SMI, the amount of carbon delivered to the roots can be greatly enhanced. Statistically higher fresh shoot weight, root weight, dry shoot and dry root mass were recorded in SMI over conventional method (Fig. 1). One possible explanation for the variance in the number of leaves in the SMI methods over conventional caused by plant densities is inter-plant competition, which rises as planting density. In contrast to direct sowing of closer spacing, Hasan et al. (2017) also assert that the maximum number of leaves per plant is achieved by providing sufficient space for both vertical and horizontal development at the proper spacing. The fresh and dry weight of shoots increased with increasing spacing, this could be as a result of less competition for light, water, and nutrients. Wider spacing plants in the SMI get adequate light and nutrients, allowing them to reach their maximum fresh weight (Hasan et al*.,* 2017). The fresh weight of roots varied significantly as a result of seedling spacing under transplanting. Under conventional methods, a higher plant density results in less light interception per plant, which lowers photosynthesis and biomass build-up. As a result, using traditional and line sowing techniques can significantly lower the amount of carbon delivered to the roots. The maximum dry shoot and root weight was discovered in SMI, however the difference in the direct sowing method is not significant. Similarly, it was shown that when the spacing increased, the dry matter content increased as fewer plants competed for nutrients during growth phases (Niraula and Timilsina, 2020).

By altering traditional crop, soil, water, and nutrient management practices, the crop intensification system improved food security, sustainability, productivity, profitability, and climate change resilience (Gupta et al., 2018). In contrast, the SMI production system in the current study improves the number of branches, root growth, plant growth, and siliqua of mustard because it makes better use of resources including moisture, nutrients, solar radiation, and leaf orientation, all of which boost photosynthesis (Pandit et al., 2022; Pandit et al., 2019). Similar findings on the enhancement of growth and yield characteristics in wheat by the SWI approach have also been proposed recently (Singh et al., 2024). The growth and yield parameters of mustard were affected significantly by methods of planting. All of the growth and yield characteristics that affected the mustard crop's seed yield were negatively impacted when direct sowing was implemented. The greatest output under SMI might be attributed to enhanced crop growth rate, maximum planting density, and better plant development, which could have resulted in an effective metabolism and provided each mustard plant with the ideal growing circumstances to optimize siliqua. This result implies that the system of mustard root intensification transplantation holds considerable promise for the cultivation of mustard varieties (Chaudhary et al., 2016; Singh et al., 2006). The higher seed yield in case of V_3 (1721.69 q/ha) might be due to more number of branches, siliquae, and test weight (Debnath et al., 2021). In *B. carinata*, transplanted crops exhibited considerably greater improved leaf-area index, number of primary and secondary branches, siliqua, oil production, protein content, and net returns compared to direct-seeded (Kaur et al. 2017). When SMI techniques are used with adequate irrigation facilities, the oxygen flow to roots is improved, which reduces the production of aerenchyma and results in a stronger, healthier root system that may have benefits for nutrient uptake (Gupta et al., 2018). Under SMI, the yield per unit area may have increased because of adequate spacing, maximum utilization of photo and thermal energy, light interception, and moisture availability by individual mustard plants, which resulted in a markedly higher accumulation of dry matter, yield attributes, and harvest index (Kumar et al., 2024). Different mustard cultivars under various crop establishment techniques had a notable impact on plant height and branches (Table 3). Among the crop establishment method SMI was most superior followed by line sowing method than conventional method. Direct sowing also showed the effect, with V_1 variety recording the highest plant height in comparison to V_3 and V_2. Direct mustard seeding, however, produced lower plant heights in all varieties

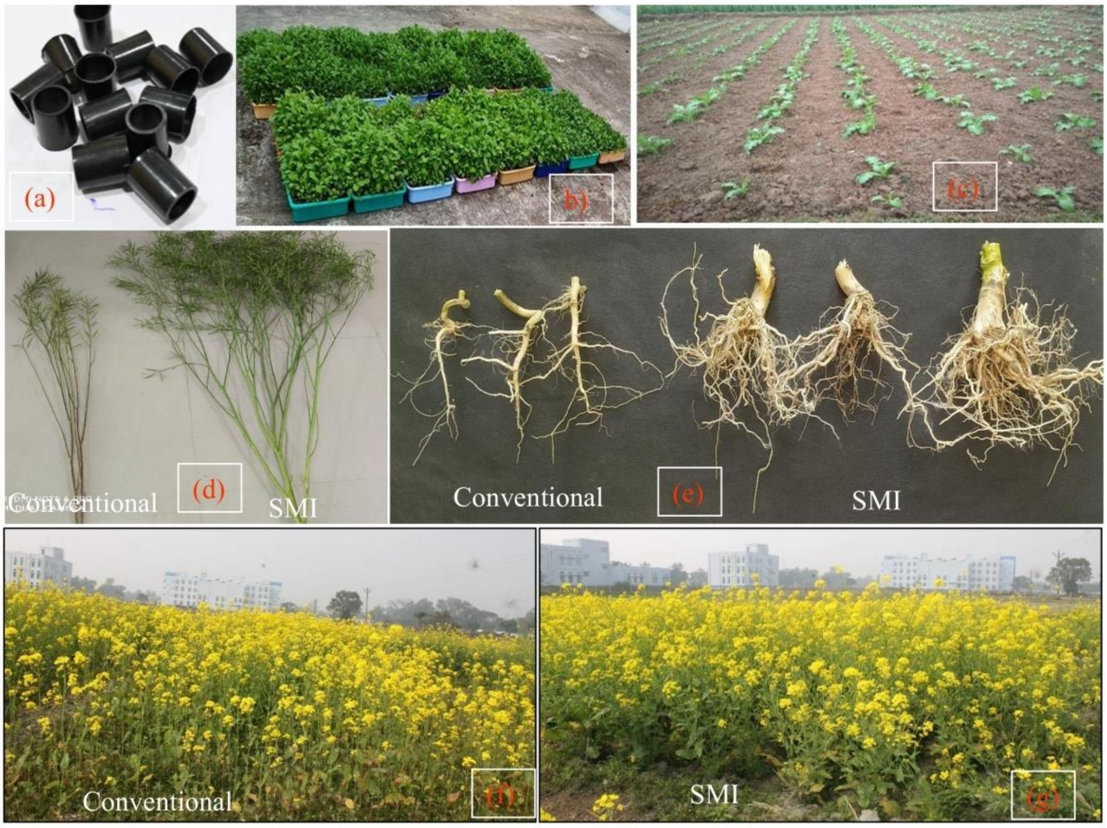

Fig. 6. Different practices of system of mustard intensification (SMI). (a) micropots (b) Nursery preparation in trays, (c) Crop geometry of SMI (45cm × 45cm), (d) plant growth comparison with conventional methods, (e) root growth comparison with conventional methods, (f) field view of conventional methods, (G) field view of SMI

when compared to transplanting SMI (Table 3); this could be because transplanting offers the additional benefit of advance growth (Al-Doori, 2013). According to Su et al. (2015), closer spacing under broad casting and line sowing techniques speeds up resource competition among plants, which has a negative impact on crop phenological development.

Among the varieties, V_3 recorded a significantly higher dry matter accumulation (52.83 g plant^{-1}) than V_2 (39.21 g plant^{-1}), but it was comparable to V_1 (50.31 g plant^{-1}). This is likely due to genetic characters that have a higher capacity to use photosynthates more efficiently for maximum leaf area index, number of primary and secondary branches plant^{-1}, and finally dry matter accumulation (Patel et al., 2022). SMI was found to have the highest dry matter accumulation (103.33 gm plant^{-1}) due to its larger photosynthetic regions, more branches, and wider plant canopy (Rathore et al., 2014; Banerjee et al., 2017). Increased dry matter accumulation under transplanted brassica was reported earlier (Rathore et al., 2022). For leaf area index maximum value recorded in V_3 (4.64) (Table 4). Adoption of SMI with wide spacing in the current study yielded statistically greater LAI than the traditional cultivation approach**.** Similar trends in LAI enhancement under transplanting techniques were also observed by Rana et al. (2020). Furthermore, a wider row arrangement in transplanting method resulted in a greater leaf area per plant than the high plant density and narrow row arrangement of direct sowing method (Singh et al*.,* 2024). Crop growth rate (g m^{-2} day^{-1}) was significantly influenced by various sowing methods and varieties. CGR increased with the advancement of crop growth and planting methods (Lallu et al*.,* 2010). Mustard seeded on SMI had the highest crop growth rate among the other sowing techniques. The harvest index of variety V_2 was substantially higher. The maximum harvest index from conventional planting was statistically comparable to that from transplanting geometry (Chaudhary et al*.,* 2016). The production efficiency of mustard cultivation significantly achieved from the SMI methods because of the maximum plant height, leaf area, and number of leaves, which led to a greater accumulation of photosynthates and higher output productivity (Padhan et al*.,* 2023).

4. CONCLUSIONS

In direct seeding resulted in lower growth and yield characteristics in all the varieties compared to system of mustard intensification in transplanting of mustard. The SMI is a resource-conserving technology that has been developed to enhance the mustard crop yields by improving the root length and plant growth characteristics. The SMI combined with planting density is significantly reducing the effects of plant lodging by enhancing crop growth and physiological characteristics such as LAI, DMC, and CGR. Concurrently, growing of V_3 genotypes demonstrated notable increases in mustard seed yields, as well as physiological characteristics. The correlation coefficient analysis of mustard varieties with different sowing methods resulted the traits particularly root length, plant height, number of leaf plant^{-1}, number of seed plant^{-1}, test weight and total chlorophyll content were significant and positive associated with seed yield. Compared to traditional broadcasting techniques, SMI technology saves time and prevents unnecessary seed waste. Adopting of this technology, it is an important step in the direction of oilseed production in India's old alluvial gangetic plains becoming self-sufficient.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

DATA AVAILABILITY STATEMENT

The data presented in this study are available upon request from the corresponding authors.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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