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RESEARCH ARTICLE

Optimizing sowing dates and varietal adaptation for enhanced yield and sustainable production of Mustard (*Brassica juncea*) in the trans-gangetic region of Punjab

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Abstract

The optimal timing for seeding a crop is essential for maximizing its genetic potential, as it provides the most favorable growing conditions in terms of meteorological parameters. Delay in planting, adverse weather conditions during the flowering period, fertilization and pod formation can result in a reduction in grain production, as well as a decrease in the duration of the maturity phase, the number of siliquae plant^{-1} and the number and weight of grains. It is evident from these facts that the timing of mustard sowing has a substantial effect on its production. A field experiment was conducted at the research farm of Lovely Professional University, Jalandhar, Punjab, during the *Rabi* season of 2023-2024, in consideration of these facts. The treatments were comprised of five varieties {V_1 (GSC-07), V_2 (Laxmi-846), V_3 (Durgamani), V_4 (Gujarat Mustard-2) and V_5 (RH-119)} that were replicated thrice under FRBD (Factorial randomized block design). The dates of sowing were as follows: D_1 (15th October) for early sown, D_2(30th October) for mid sown and D_3 (15th November) for late sown. Data regarding yield attributing parameters and yield were obtained after the harvest. Results revealed that mostly no. of siliqua/plant was obtained with treatment combination $D_1 \times V_2$ (188.820) followed by $D_1 \times V_3$ (186.823), siliqua length (7.467cm) with $D_1 \times V_2$ followed by $D_2 \times V_2$ (7.340 cm), weight of one siliqua/plant (0.150g) by $D_1 \times V_3$ which was at par with $D_1 \times V_5$ and $D_2 \times V_1$, no. of seeds/siliqua (21.233) by $D_1 \times V_2$ followed by $D_2 \times V_2$ (20.177), weight of seeds/siliqua (0.090g) by $D_1 \times V_2$ which was at par with $D_2 \times V_1$, test weight (6.967g) by $D_1 \times V_2$ followed by $D_2 \times V_2$ (6.767). Under the agroclimatic conditions of the experimental area, the most effective method of cultivation was the early seeding (15th October) and the mid sowing (30th October) of the Laxmi-846 (V_2) variety.

Keywords : agronomic practices; mustard; responsible consumption and production; sowing date optimization; varietal adaptation; yield performance

Introduction

The potential of mustard crops is significant, as they are the third-largest source of edible oil in the world, following palm (*Elaeis guineensis Jacq*.) and soybean (*Glycine max* (L.) Merr.) (Fig. 1). Mustard is a critical component of the nation's oil seed economy. Mustard seeds are composed of 20-25 % protein and 40-45 % oil (1). India is responsible for 20 % of global production and 28 % of global rapeseed-mustard acreage (2). The rapeseed-mustard sector is significantly influenced by India, the world's third-largest producer, following China and Canada (Fig. 2). The area, yield and productivity of this crop in India are 6.9 million hectares, 8.78 million metric tons and 1281 kilograms ha^{-1}, respectively (3). Although India occupies an important position on the global oilseed production and acreage map, there is a significant gap between its actual production and its potential (4). Mustard is most frequently cultivated in temperate climates. It is also grown as a cold-weather crop in certain tropical and subtropical regions. According to reports, Indian mustard can endure soil pH levels between 4.3 and 8.3, temperatures varying from 6 to 27 °C and 500 to 1200 mm of precipitation annually (5). The time of sowing is one of the most significant non-monetary variables that substantially impact the productivity of seeds and oils. Rapeseed and mustard are typically sown in north India between the first week of October and the middle of November (2). Therefore, the timing of mustard cultivation is of the utmost importance. The yield of mustard is reduced when sowing is delayed due to its chilling effects on plant development, flowering duration, seed formation and seed size. Timely fertilization enables the crop plant to complete both the vegetative and reproductive growth periods with a higher yield. In contrast, crops that are planted later are at risk of aphid damage during the flowering and pod development phases, as well as low temperatures during germination and the early

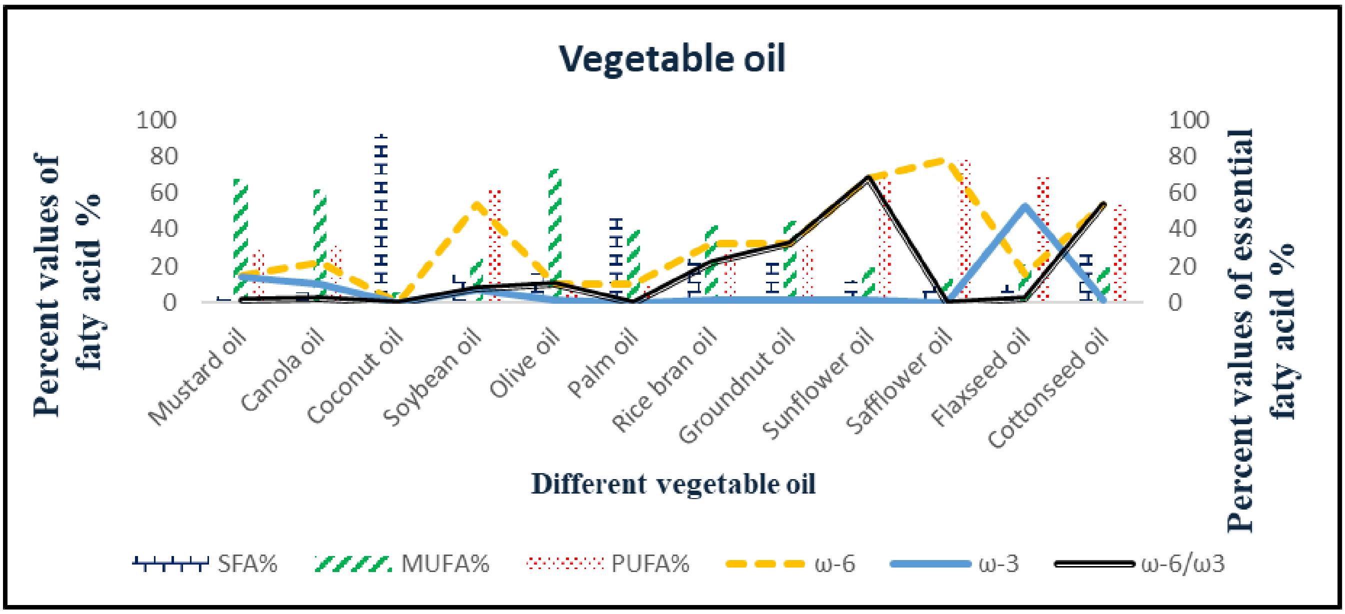

Fig. 1. Representing the different vegetable oils' percent value of essential fatty acids.

stages of growth. Consequently, the crop is susceptible to aphid attacks if the sowing process is delayed. The optimal sowing period is essential for the complete utilization of a variety's genetic potential, as it provides the optimal growing conditions, which include temperature, light, humidity and rainfall. The crop's growth period should be aligned with optimal environmental conditions to optimize growth and yield (6). To overcome the aforementioned constraints in mustard production, the present research program aimed to determine the optimal planting time and select a variety that would generate the highest yield in the Jalandhar district of Punjab, taking into account a variety of yield-attributing characteristics.

Materials and Methods

Experimental site

The research experiment was performed during the cropping season, 2023-2024 at the research farms of Lovely Professional University, Jalandhar, Punjab, India. Geographically, the farm is located at latitude 31.2554°N, longitude 75.7058°E, with an elevation of 235 m above the mean sea level.

Sowing and agronomic practices

The land was prepared by tilling once by tractor driven cultivar, one harrowing was done by Disc harrow to obtain the desirable fine seed bed. A uniform dose of RDF (100:60:40 kg NPK ha^{-1}) was applied. After a month of emergence of crop for all the three dates of sowing, thinning was carried out, weed control was done manually and no chemicals were used. The experimental farm was irrigated during the growing seasons and harvesting was done at crop maturity. Five varieties/strains namely GSC-07(V_1), Laxmi-846 (V_2), Durgamani (V_3), Gujarat Mustard-2 (V_4) and RH-119 (V_5) were sown at three planting dates, early (15th October), mid (30th October) and late (15th November). This was done to find out the maximum yield and yield attributes with respect to the three dates of sowing. Prior to sowing, a laboratory germination test was conducted for each mustard variety in the Agronomy Laboratory of Lovely Professional University to determine seed viability and establish the appropriate seeding rate. For each variety, a sample of ten seeds was selected and placed on moist filter paper in petri dishes under controlled temperature and light conditions. The seeds were monitored over a period of 7-10 days and the number of seeds that successfully germinated was recorded. Germination was defined as the emergence of a radicle (Fig. 3). The germination percentage was calculated using the following formula

$$\text{Germination (\%)} = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds tested}} \times 100$$

Design

The experiment was laid out in Factorial Randomized Block Design (FRBD) with two factors and three replications. The treatments comprised of three dates of sowing treated as a main factor and five different varieties treated as sub-factor. A total of 45 plots were laid out with the net plot size of 5×4 m for each entry. The row to row spacing was kept as 30 cm while 10 cm was plant to plant spacing. The crop was sown with the seed rate of 4-6 kg ha^{-1} at depth of 3-4 cm.

Observation and analysis

Observations such as number of siliquae plant^{-1}, length of siliqua plant^{-1} (cm), weight of one siliqua plant^{-1} (g), number of seeds siliqua^{-1}, weight of the seeds siliqua^{-1} (g), test weight (g), seed yield (q ha^{-1}), stover yield (q ha^{-1}), biological yield (q ha^{-1}) and Harvest Index (HI %) were recorded after the harvest. The seed yield was calculated by weighing the seeds harvested from each plot and converted to q ha^{-1}. Using sun drying, the stover yield (q ha^{-1}) was determined. Biological yield and HI (%) was recorded using the following formulae.

$$\text{Biological yield (q ha}^{-1}\text{)} = \text{seed yield} + \text{stover yield}$$

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

The biological yield from each plot was computed by adding seed yield to stover yield of the individual plot and expressed in q ha^{-1}. The HI for each plot was calculated from the ratio of seed yield to biological yield and expressed in terms of percentage (7). Five plants were sampled for every observation. Analysis of Variance (ANOVA) from the data was employed to compute variable effects in both the factors and their interaction. Significant differences between means of sowing dates, varieties and interactions were determined by CD. Treatment means were compared at the 5 %, 1 %, 0.1 % level of significance (P=0.05, P=0.01, P=0.001) using CD and hence results based on pooled analysis are presented here to draw logical inferences. Pearson correlation was employed to ascertain the link between the yield and yield parameters at 5 % significance level, evaluating both significant and non-significant parameters. Principal Component Analysis (PCA) was done using GRAPES software.

Results and Discussion

Pre-sowing germination test

The results of germination indicated that variety Laxmi-846 (V_2) exhibited the highest germination rate (100 %), varieties Durgamani (V_3) and RH-119 (V_5) recorded identical germination percentages, with 90 % of the seeds successfully germinating followed by GSC-07 (V_1) which displayed a germination percentage of 80 % while variety Gujarat Mustard-6 (V_4) exhibited the lowest germination rate (70 %). The differences in germination percentages observed among the mustard varieties suggest variability in seed viability which could significantly influence early stand establishment and subsequent yield.

Yield attributes of mustard

Number of siliquae plant^{-1}: Under early sowing (D_1), the highest number of siliquae per plant (184.002) was observed, followed by the right time sowing (D_2) and late sowing (D_3). Laxmi-846 (V_2) exhibited the maximum siliqua count (168.144) among the varieties, while Gujarat Mustard-6 (V_4) recorded the lowest (155.064). The highest siliquae number (188.820) was achieved by the combination of early sowing (D_1) with Laxmi-846 (V_2), while the lowest siliquae count (135.447) was achieved by the combination of late sowing (D_3) with Gujarat Mustard-6 (V_4) (Table 1). The varietal characteristics of Laxmi-846 (V_2) may be responsible for its consistently high siliqua count across all sowing dates, which indicates its adaptability to early, timely and late planting. Consequently, the fertilization date had a negligible effect on the production of siliqua for this variety. These results are consistent with those reported by (8).

Length of siliqua per plant (cm) : The maximum length of siliqua (6.462 cm) was recorded with D_1 planting time, which was more than D_2 and D_3. Laxmi-846 (V_2) exhibited the longest siliqua (6.918 cm), followed by Durgamani (V_3) and RH - 119 (V_5), which appeared to have statistically identical siliqua lengths. Treatment interactions indicated that the longest siliqua (7.467 cm) was observed with $D_1 \times V_2$, while the shortest (3.557 cm) was identified with $D_3 \times V_4$ (Table 1). Genetics, environmental conditions, agronomic practices and stress factors all contribute to the multifactorial trait of siliqua length. It was discovered that the siliqua length in Gujarat Mustard-2 (V_4) is reduced because of late sowing. This implies that the optimal sowing time for this variety is not D3. BARI Sarisha-14 has yielded comparable results (9).

Weight of one siliqua per plant (g): The highest (0.141 g) weight of siliqua was recorded with early sowing (D_1) while sowing of 30th October produced the lowest (0.123 g) siliqua weight. GSC-07(V_1) produced the highest (0.139 g) siliqua and the lowest (0.123 g) siliqua was recorded by RH-119 (V_5). In terms of treatment interactions, $D_1 \times V_3$, $D_1 \times V_5$ and $D_2 \times V_1$ had statistically identical maximum (0.150 g) siliqua weight and minimum (0.103 g) was recorded in $D_2 \times V_5$(Table 1). Siliqua weight was significantly lowest with the mid sowing (D_2) which was also revealed from the interaction effect. Since different mustard varieties have different genetic compositions, their siliqua characteristics differ (10). This may be attributed to the varietal trait that GSC-07 has longer and heavier siliqua and RH-119 has shorter and lighter siliqua. The current findings are in line with previous results (11).

No. of seeds per siliqua: D_1 recorded the maximum (18.869) number of seeds per siliqua followed by D_2. Among the mustard varieties, Laxmi-846 (V_2) generated the maximum (19.404) number of seeds and the minimum (14.078) was marked with Gujarat Mustard-2 (V_4). Interestingly, Laxmi-846 (V_2) recorded the highest (21.233) seed number at both early (D_1) as well as mid planting (D_2). The lowest (11.583) seed number was noted with Gujarat Mustard-2 (V_4) at late planting (D_3) (Table 1). Late sowing resulted in the decrease in seed number for all the mustard varieties. High temperatures and long days hastened the pod development phase, resulting in faster pod maturity and reduced seed number (12).

Weight of seeds per siliqua (g): Early planting of 15th October (D_1) produced the highest (0.072g) seed weight per siliqua followed by D_2 and D_3. Laxmi-846 (V_2) produced the maximum (0.069 g) seed weight per siliqua followed by Durgamani (V_3) and RH-119 (V_5) which seemed to have statistically identical seed weight per siliqua. In case of interaction effect maximum (0.090g) seed weight per siliqua was noted with $D_1 \times V_2$ and the minimum (0.023g) was obtained by Gujarat Mustard-2 (V_4) with D_3 planting time (Table 1).

Seed weight per siliqua was obtained lowest for the late sowing (D_3). The reason for the lower seed weight may be attributed to the changes in weather parameters, temperature and day length variations that affected crop development, which in turn caused poor seed filling in siliqua and a drop in seed weight siliqua^{-1} (13).

Test weight (g): Planting on October 15th (D_1) yielded the heaviest (4.540) and boldest grain, whereas the late planting on November 15th (D_3) yielded the lightest (3.944) seed weight. Among the varieties, Laxmi-846 (V_2) produced the highest (4.568) test weight and the lowest (3.572) thousand grain weight was recorded by Gujarat Mustard-2 (V_4). Laxmi-846 (V_2) planted at D_1 and Durgamani (V_3) planted at D_1 both exhibited statistically identical maximum (4.923), (4.893) test weight over all other treatment amalgamations. Combined effect of $D_2 \times V_4$ and $D_3 \times V_4$ produced minimum (3.417) test weight which seemed to be statistically identical. Test weight

Table 1. Yield attributes of mustard under various treatments and their amalgamation

Treatments	No. of siliqua/ plant	Siliqua length (cm)	Weight of one siliqua/plant (g)	No. of seeds/ siliqua	Weight of seeds / siliqua(g)	Test weight (g)
Sowing Dates						
D_1(15th Oct.)	184.002a	6.462a	0.141a	18.869a	0.072a	4.540a
D_2 (30th Oct.)	158.701b	5.896b	0.123c	17.700b	0.053b	4.085b
D_3 (15th Nov.)	142.946c	4.725c	0.133b	14.308c	0.037c	3.944c
CD (P = 0.05)	0.82	0.38	0.01	0.55	0.00	0.05
SEm±	0.28	0.13	0.00	0.19	0.00	0.02
Treatments	**No. of siliqua/ plant**	**Siliqua length (cm)**	**Weight of one siliqua/plant (g)**	**No. of seeds/ siliqua**	**Weight of seeds / siliqua(g)**	**Test weight (g)**
Variety						
GSC-07 (V_1)	159.158d	5.166c	0.139	15.924d	0.044c	4.058d
Laxmi-846 (V_2)	168.144a	6.918a	0.132	19.404a	0.069a	4.568a
Durgamani (V_3)	164.929b	6.204b	0.133	18.174b	0.060b	4.459b
Gujarat Mustard-2 (V_4)	155.064e	4.218d	0.134	14.078e	0.040c	3.572e
RH-119 (V_5)	162.120c	5.967b	0.123	17.213c	0.056b	4.291c
CD (P = 0.05)	1.06	0.50	-	0.70	0.00	0.07
SEm±	0.37	0.17	0.00	0.24	0.00	0.02
Sowing Time × Variety	**No. of siliqua/ plant**	**Siliqua length (cm)**	**Weight of one siliqua/plant (g)**	**No. of seeds/ siliqua**	**Weight of seeds siliqua(g)**	**Test weight (g)**
$D_1 \times V_1$	181.740d	5.833	0.130bcd	17.997	0.063	4.327d
$D_1 \times V_2$	188.820a	7.467	0.147ab	21.233	0.090	4.923a
$D_1 \times V_3$	186.823b	7.167	0.150a	19.623	0.083	4.893a
$D_1 \times V_4$	178.750e	4.933	0.130bcd	16.793	0.053	3.883h
$D_1 \times V_5$	183.877c	6.910	0.150a	18.697	0.070	4.673b
$D_2 \times V_1$	155.850i	5.597	0.150a	16.763	0.043	4.033fg
$D_2 \times V_2$	166.320f	7.340	0.127cde	20.177	0.067	4.457c
$D_2 \times V_3$	161.907g	6.190	0.110ef	19.200	0.057	4.337d
$D_2 \times V_4$	150.997j	4.163	0.127cde	13.857	0.043	3.417i
$D_2 \times V_5$	158.433h	6.190	0.103f	18.503	0.053	4.180e
$D_3 \times V_1$	139.883m	4.067	0.137abc	13.013	0.027	3.813h
$D_3 \times V_2$	149.293j	5.947	0.123cde	16.803	0.050	4.323d
$D_3 \times V_3$	146.057k	5.257	0.140abc	15.700	0.040	4.147ef
$D_3 \times V_4$	135.447n	3.557	0.147ab	11.583	0.023	3.417i
$D_3 \times V_5$	144.050l	4.800	0.117def	14.440	0.043	4.020g
CD (P = 0.05)	1.83	-	0.02	-	-	0.12
SEm±	0.63	0.30	0.01	0.42	0.00	0.04
CV	0.68	9.02	8.62	4.30	15.96	1.69

seemed to be influenced by both the factors, sowing date and variety. Both sowing dates and mustard variety selection play critical roles in determining the test weight of mustard. Sowing at an optimal time with a variety that aligns well with the local climate and growing conditions generally leads to higher test weights, while delayed sowing or the choice of unsuitable varieties can result in lower seed weights (14).

Yield and yield characters

Seed yield (q/ha): The highest (21.181 q/ha) seed yield was obtained by D_1 planting followed by D_2 and lowest (16.285) by D_3. Relatively maximum (22.139 q/ha) seed yield was recorded in Laxmi-846 (V_2) followed by Durgamani (V_3) and RH-119 (V_5). Interaction effects exhibited the maximum (24.713q/ha) (22.403q/ha) yield of Laxmi-846 over D_1 and D_2 and Durgamani (V_3) over D_1 (22.677q/ha) planting time. Gujarat Mustard-2 (V_4) produced minimum (12.590q/ha) yield in the later sowing time (D_3) (Table 2). Our findings are like those reported previously which indicate that late planting leads to possible decrease in the seed yield as late-sown mustard crops have a shorter growing period, meaning less time for vegetative growth before the flowering and seed-setting stages, which limits biomass and yield potential. Also, late sowing exposes the crop to higher temperatures during critical growth stages which can lead to premature flowering and quicker seed maturation, reducing seed size and quality. Late sowing can increase susceptibility to pests (like aphids) and diseases due to higher population levels in warmer, late-season conditions. These stresses can significantly affect seed yield (14).

Stover yield (q/ha): Early planting (D_1) noted the highest (27.527) amount of stover yield followed by mid planting (D_2). Among the varieties, the maximum (27.683) stover yield was produced by Laxmi-846 (V_2) followed by Durgamani (V_3) and RH-119 (V_5). Combined effects revealed that most (30.953) stover yield was gained with $D_1 \times V_2$ and least (17.477) with $D_3 \times V_4$ (Table 2).

Different mustard varieties have distinct genetic potential for growth, biomass accumulation and stover yield. As Laxmi-846 (V_2) generated the highest stover yield for the early planting D_1 compared to the mid and late sowing dates (D_2 and D_3). So, this can be attributed to the planting schedule and varietal adaptation. Early sowing allows mustard plants to grow during periods with better light conditions, leading to enhanced photosynthesis and more biomass accumulation whereas late sowing can shorten the time available for the crop to capture light, reducing growth and stover yield. Moreover, late-sown crops often experience higher temperatures, which accelerate the transition from vegetative growth to reproductive phases, shortening the period available for stover accumulation (15, 16).

Biological yield (q/ha)

The highest (48.708 q/ha) biological yield was gained by early planting date (D_1) and D_3 generated the lowest (35.519 q/ha) biological yield. The maximum (49.822 q/ha) biological yield was produced by Laxmi-846 (V_2) followed by Durgamani (V_3) while minimum (35.903 q/ha) biological yield was seen with

Table 2. Yield and yield characters under different treatments and their amalgamation

Treatments *Sowing Dates*	Seed yield (q/ha)	Stover yield (q/ha)	Biological yield (q/ha)	HI (%)
D_1(15th Oct.)	21.181^a	27.527^a	48.708^a	43.437
D_2 (30th Oct.)	18.849^b	23.547^b	42.397^b	44.434
D_3 (15th Nov.)	16.285^c	21.235^c	37.519^c	43.263
CD (P = 0.05)	0.71	0.72	1.18	-
SEm±	0.25	0.25	0.41	0.35
Treatments *Variety*	**Seed yield (q/ha)**	**Stover yield (q/ha)**	**Biological yield (q/ha)**	**HI (%)**
GSC-07 (V_1)	16.860^d	22.369^d	39.229^d	42.931
Laxmi-846 (V_2)	22.139^a	27.683^a	49.822^a	44.406
Durgamani (V_3)	20.584^b	25.988^b	46.572^b	44.244
Gujarat Mustard-2 (V_4)	15.504^e	20.399^e	35.903^e	43.140
RH-119 (V_5)	18.771^c	24.076^c	42.847^c	43.836
CD (P = 0.05)	0.92	0.93	1.52	-
SEm±	0.32	0.32	0.53	0.46
Treatments *Sowing Dates× Variety*	**Seed yield (q/ha)**	**Stover yield (q/ha)**	**Biological yield (q/ha)**	**HI (%)**
D_1×V_1	19.383	25.593	44.977	43.087
D_1×V_2	24.713	30.953	55.667	44.380
D_1×V_3	22.677	29.373	52.050	43.560
D_1×V_4	18.330	24.270	42.600	43.033
D_1×V_5	20.803	27.443	48.247	43.123
D_2×V_1	16.827	21.573	38.400	43.827
D_2×V_2	22.403	27.503	49.907	44.880
D_2×V_3	20.520	25.803	46.323	44.300
D_2×V_4	15.593	19.450	35.043	44.490
D_2×V_5	18.903	23.407	42.310	44.673
D_3×V_1	14.370	19.940	34.310	41.880
D_3×V_2	19.300	24.593	43.893	43.957
D_3×V_3	18.557	22.787	41.343	44.873
D_3×V_4	12.590	17.477	30.067	41.897
D_3×V_5	16.607	21.377	37.983	43.710
CD (P = 0.05)	-	-	-	-
SEm±	0.55	0.55	0.91	0.79
CV	5.08	3.98	3.68	3.13

Values in a column having different letter (s) differ significantly at 5 %, 1 % and 0.1 % level of probability according to CD, Minimum value between the interaction, NS, not significant, *, P < 0.05, **, P < 0.01 and ***, P < 0.001 by analysis of variance with randomized complete block design

Gujarat Mustard-2 (V_4). Treatment combinations showed that highest (55.667 q/ha) biological yield was seen with D_1×V_2, followed by D_1×V_3 and the least (17.477 q/ha) was marked with D_3×V_4 (Table 2).

Since Laxmi-846 (V_2) exhibited the highest biological yield under early planting (D_1). This may be because of the varietal adaptability to different environmental conditions and their genetic potential which allows them to exhibit varying capacities for biomass production (17). In addition, early sowing extends the growing period, allowing mustard plants to fully utilize available sunlight, moisture and nutrients. This longer vegetative and reproductive phase contributes to higher biomass accumulation and consequently, higher biological yield. In contrast, late sowing can expose mustard to warmer temperatures during the reproductive phase, shortening the growth period and reducing biomass production (18). The biological yield of mustard under different planting dates and reported a decline in the biological yield under late planting (16).

Harvest Index (HI)

Mid planting (D_2) induced a significantly maximum (44.434 %) HI over D_1 and D_3 planting. Contrary, Laxmi-846 (V_2) exhibited highest (44.406 %) HI while the lowest (42.931 %) was generated by GSC-07 (V_1). In terms of combination effects, the highest (44.38 %) HI was acquired by D_2×V_2 and D_3×V_1 marked the lowest (41.88 %) HI. As GSC-07 (V_1) noted the least HI for the late planting date (D_3). Late sowing tends to reduce the harvest index in mustard by diminishing both the biomass and the economic yield. The extent of the reduction depends on the specific variety and its adaptability to heat stress or shorter growing periods (16, 19).

Correlation among different yield attributes

Table 3 represents a correlation matrix that displays the correlation coefficients between multiple variables, which shows the strength and direction of the relationship between each pair of variables. This table provides insight into how strongly yield attributes are related to each other and to the yield. Each cell in the table represents the correlation coefficient (rr) between two traits. The values range from -1 to +1. Positive values indicate a direct relationship (as one trait increases, the other tends to increase). Negative values indicate an inverse relationship. Values closer to ±1 indicate strong correlations, while values close to 0 suggest weak or no correlation. (Fig. 4) figured that number of siliquae per plant had a highly significant and positive correlation with siliqua length per plant (0.716), number of seeds per siliqua (0.789), weight of seeds per siliqua (0.852), test weight (0.746), seed yield (0.779), stover yield (0.845) and biological yield (0.825). But it had a positive nonsignificant correlation with weight of one siliqua per plant and harvest index. Siliqua length per plant

Table 3. Pearson correlation between yield and yield contributing characters

Parameters	No. of siliqua/ plant	Siliqua length/ plant (cm)	Weight of one siliqua/plant (g)	No. of seeds/ siliqua	Weight of seeds/ Siliqua (g)	Test weight (g)	Seed yield (q/ha)	Stover yield (q/ha)	Biological yield (q/ha)	HI (%)
No. of siliqua/ plant	1	0.716***	0.212NS	0.789***	0.852***	0.746***	0.779***	0.845***	0.825***	0.089NS
Siliqua length/ plant (cm)		1	0.052NS	0.864***	0.792***	0.891***	0.881***	0.889***	0.896***	0.267NS
Weight of one siliqua/plant (g)			1	-0.016NS	0.166NS	0.153NS	0.056NS	0.086NS	0.073NS	-0.082NS
No. of seeds siliqua				1	0.83***	0.86***	0.913***	0.906***	0.921***	0.316*
Weight of seeds/ siliqua (g)					1	0.814***	0.863***	0.871***	0.878***	0.268NS
Test weight (g)						1	0.896***	0.936***	0.929***	0.174NS
Seed yield (q/ha)							1	0.951***	0.986***	0.416**
Stover yield (q/ha)								1	0.989***	0.168NS
Biological yield (q/ha)									1	0.308*
HI (%)										1

NS, not significant; *, P < 0.05, **, P < 0.01 and ***, P < 0.001

implied highly significant and positive correlation with number of seeds per siliqua (0.864), weight of seeds per siliqua (0.792), test weight (0.891), seed yield (0.881), stover yield (0.889) and biological yield (0.896) but a non-significant and positive correlation with weight of one siliqua per plant and HI. Weight of one siliqua per plant had a non-significant positive correlation with weight of seeds per siliqua, test weight, seed yield, stover yield and biological yield. However, a non-significant negative correlation was established with number of seeds per siliqua (-0.016) and HI (-0.082). Number of seeds per siliqua showed a highly significant and positive correlation with weight of seeds per siliqua (0.83), test weight (0.86), seed yield (0.913), stover yield (0.906) and biological yield (0.921) and a significant, positive correlation with HI (0.316). Weight of seeds per siliqua had a highly significant and positive correlation with test weight (0.814 g), seed yield (0.863 q/ha), stover yield (0.871 q/ha) and biological yield (0.878 q/ha) but a nonsignificant and positive correlation with HI. Test weight established a highly significant and positive correlation with seed yield (0.896 q/ha), stover yield (0.936 q/ha) and biological yield (0.929 q/ha) but a nonsignificant positive correlation with HI (0.174 %). Seed yield implied a highly significant and positive correlation with stover yield (0.951 q/ha) and biological yield (0.986 q/ha) and a significant positive correlation with HI (0.416 q/ha). Stover yield had a highly significant and positive correlation with biological yield (0.989 q/ha) and a nonsignificant positive correlation with harvest index. Biological yield implied a significant positive correlation with HI (0.308) (20).

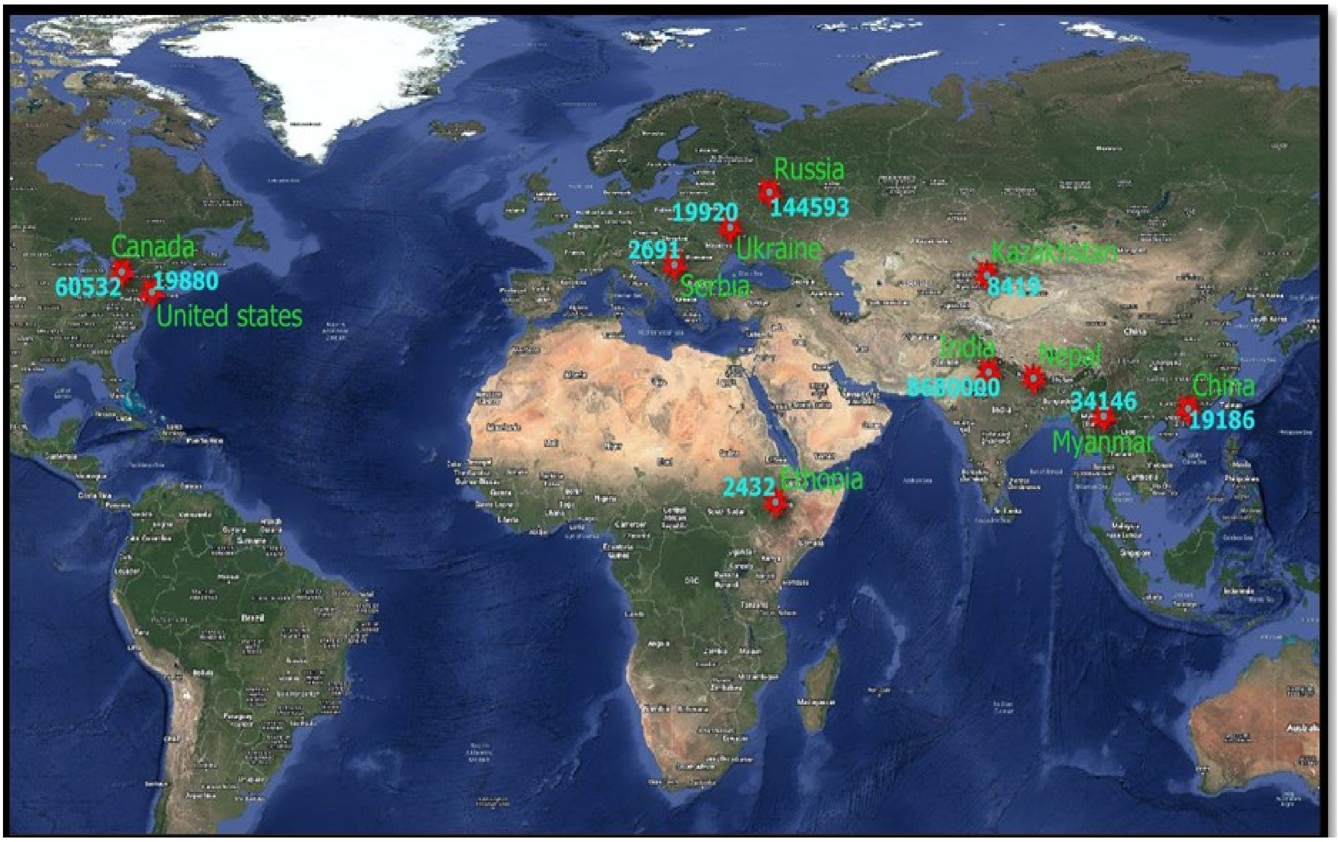

Fig. 2. Representing the world mustard producing countries with their production in Tonnes.

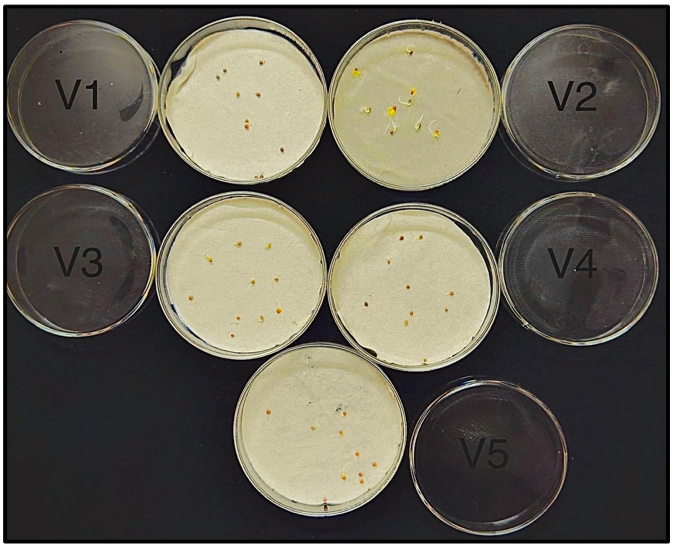

Fig. 3. Representing the emergence of radicle in Mustard varieties during germination test.

Principal Component Analysis (PCA)

Fig. 5 image represents a PCA biplot, commonly used to diminish data dimensionality and illustrate the variation explained by various factors in a two-dimensional framework. The centre signifies a connection space. Points nearer to the circumference of the circle have a stronger correlation with the principal components (PC1 and PC2, generally the axes). Points proximate to the origin have a modest correlation. The variables, including $D_1 \times V_2$ (number of siliquae $plant^{-1}$), $D_1 \times V_3$ (weight of seeds $siliqua^{-1}$), $D_1 \times V_2$ (length of siliqua $plant^{-1}$) and $D_1 \times V_2$ (number of seeds $siliqua^{-1}$), positively influence the first principal component (horizontal axis), indicating that these qualities likely exhibit concurrent variation in the same direction. However, the variable (weight of one siliqua $plant^{-1}$) with longer arrow exerts a more significant impact on the data structure. These characteristics are crucial for elucidating the variance along PC1. Variables that align in the same direction exhibit positive correlations, whereas those that diverge exhibit negative correlations. Path coefficient analysis allows for the comparison of the component elements based on their relative contributors and is more helpful in distinguishing between the direct and indirect impacts of correlation (21). Fig. 6 biplot illustrates the correlations among various yield-related variables (e.g., test weight, seed yield, stover yield, biological yield and harvest index) and their contributions to the fundamental framework of the data (principal components). The variable (HI) with longer arrow exerts a more significant impact on the data structure. The proximity and orientation of arrows provide insight into the interrelationship of the variables (22).

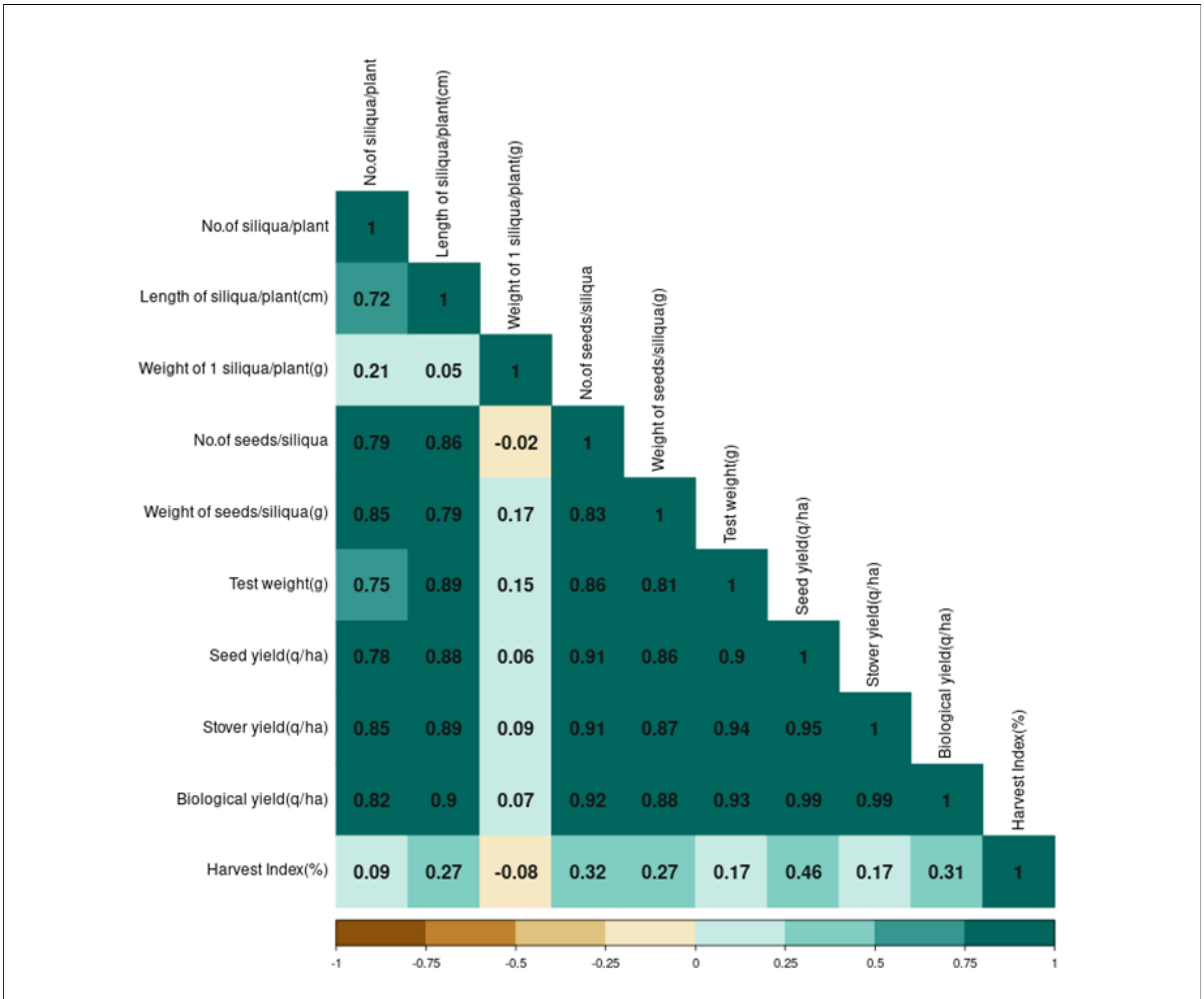

Fig. 4. Correlation heat map between yield and yield attributes of Mustard illustrating the pairwise correlations among several yield characteristics. Every column in the matrix denotes the correlation coefficient, which ranges from -1 to 1, between two parameters. Dark green signifies a strong positive correlation (+1 indicates a perfect positive correlation). Brown signifies a strong negative correlation (-1 denotes a perfect negative correlation). Slight lighter shades in the center indicate lower interactions, approaching 0 (no correlation).

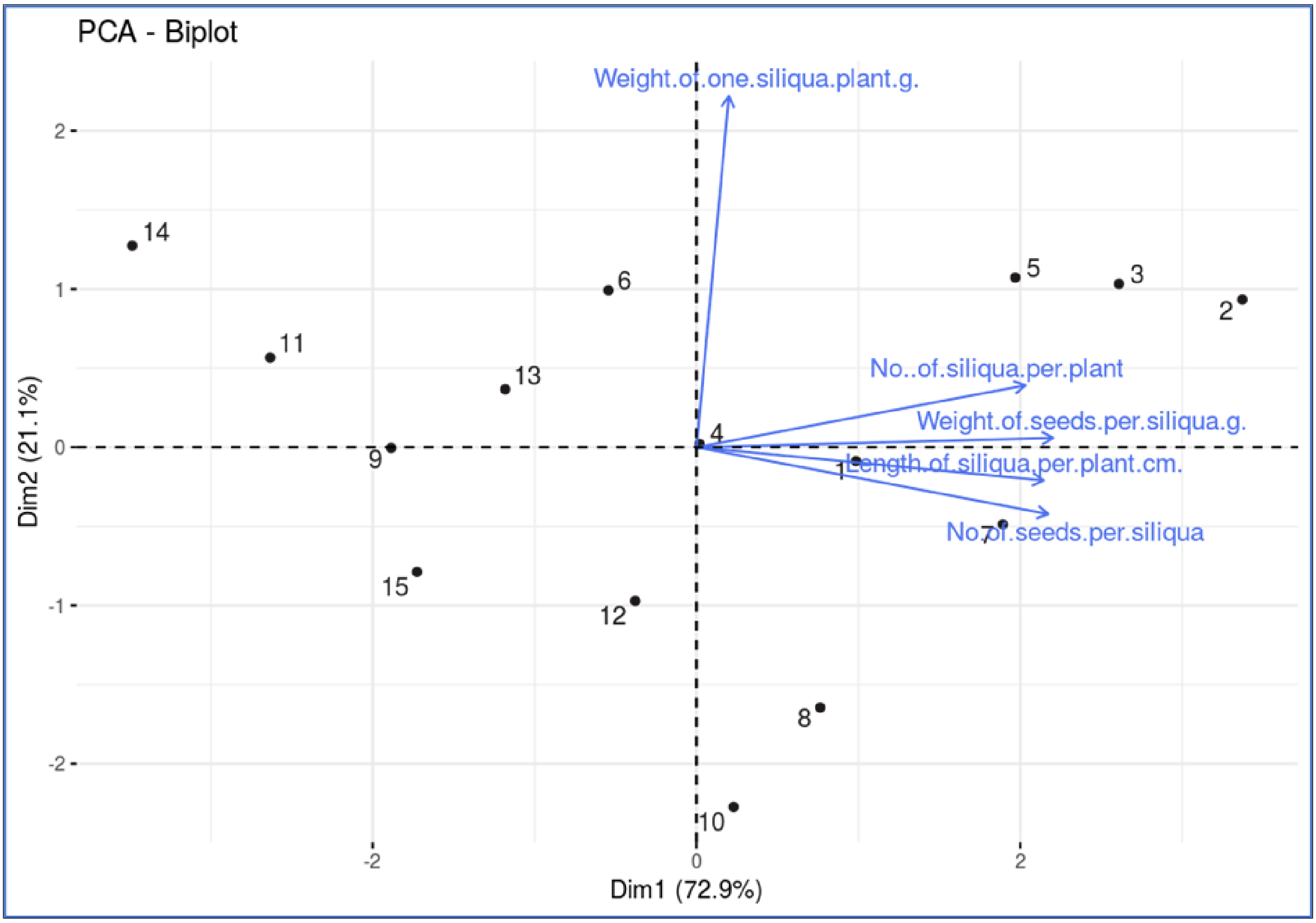

Fig. 5. Principal Component Analysis (PCA) biplot showing the relationship between yield attributes and the two principal components. The arrows represent the following traits: No. of siliqua/plant, length of siliqua/plant, weight of 1 siliqua/plant, no. of seeds/siliqua, weight of seeds/siliqua and test weight. The direction and length of the arrows indicate the contribution of each attribute to the principal components.

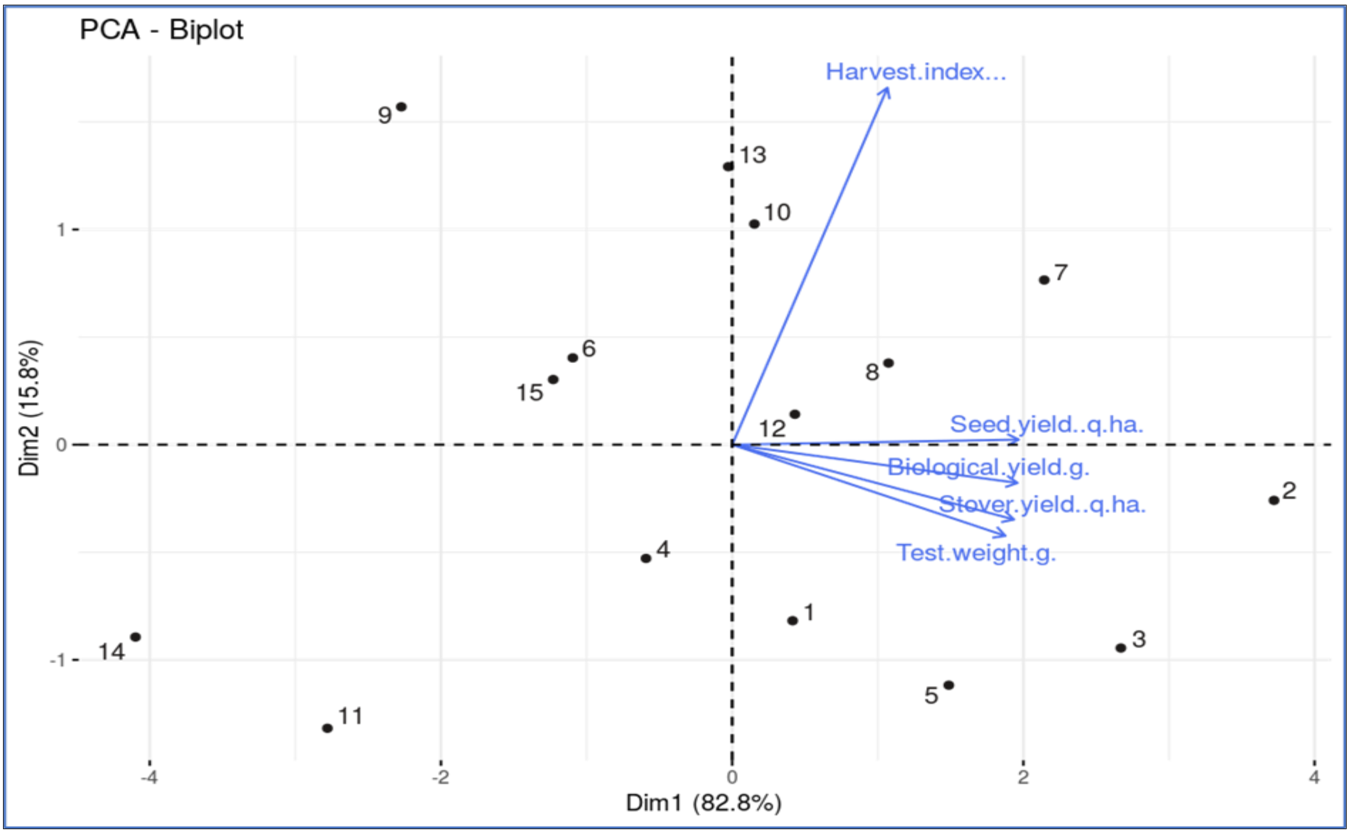

Fig. 6. PCA biplot, showing the relationship between various yield and yield-related characters and their contributions to the principal components. The arrows represent the following characters: Test weight, seed yield, stover yield, biological yield and harvest index. The direction and length of the arrows indicate the contribution of each character to the principal components.

Conclusion

Most yield attributes recorded highest under planting on October 15th, according to our results. Additionally, varietal adaptability was also seen. Laxmi-846 achieved the highest biological yield at every sowing time, indicating a broad range of adaptation during the planting periods. This research has shown that both sowing date and mustard variety has significant impact on yield parameters and yield. These findings provide actionable recommendations for improving mustard crop productivity through informed decision-making. Although our study is limited, future research that includes a wider range of environmental factors and agronomic practices will further enhance the applicability of these recommendations across different mustard-growing regions.

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Authors' contributions

IM performed the fieldwork, collected data and wrote the paper, AS analysed the data and prepared figures and SS reviewed 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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