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Original article

Allometric dynamics of *Sinapis alba* under different ecological conditions

Ghulam Muhammad [a], Abdul Manaf [a,*], Fayyaz-ul-Hassan [a], Azeem Khalid [b], Ahmad Sher [c], Carol J. Lovatt [d], Asad Syed [e], Ali H. Bahkali [e], Abdallah M. Elgorban [e], Abdul Qayyum [f,*]

[a] Department of Agronomy, Pir Mehr Ali Shah-Arid Agriculture University Rawalpindi, Rawalpindi 46300, Pakistan
[b] Department of Environmental Sciences, Pir Mehr Ali Shah-Arid Agriculture University Rawalpindi, Rawalpindi 46300, Pakistan
[c] Department of Agricultural and Food Sciences, University of Bologna, 40127 Bologna, Italy
[d] Department of Botany & Plant Sciences, University of California, Riverside, USA
[e] Department of Botany and Microbiology, College of Science, King Saud University, P.O. 2455, Riyadh 11451, Saudi Arabia
[f] Department of Agronomy, The University of Haripur, Haripur 22620 Pakistan

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ABSTRACT

Objectives: The indigenous oilseed crops are facing the problems of insects, diseases attack with poor yield potential. Canola needs high water requirement and also > 50 % shattering losses. Therefore, farmers are compelled to cultivate alternative crops. *Sinapis alba* is the best replacement of winter rapeseed due to superior phenotypic plasticity for dry temperate climate like Pakistan Pertinent sowing time augments the soil and climatic resources efficiency in a specific ecological zone to expose various phenological stages for appropriate growth and development to achieve potential yield.
Methods: Field experiments were performed to appraise the suitable sowing date at three locations (NARC, SAWCRI and Talagang) in Pothwar plateau of Pakistan. Six sowing dates from 1st October up to 15th December with fifteen days interval were quart replicated in RCBD during two 2017–18 and 2018–19. Explicated environment of various locations prudently influenced *Sinapis alba* performance and yield attributes to accomplish potential yield during both years. Among sowing dates, 15th October enormously promoted morphological development to attained maximum mean values of pods plant^{-1}, 1000-seed weight, biological yield and seed yield. Among locations, SAWCRI nurtured highest number of plants^{-2}, plant height, primary and secondary branches, pods plant^{-1}, seed pod^{-1}, 1000-seed weight, biological yield and seed yield. Variability in Agro-meteorological indices of three locations significantly influenced the interactive effect of year × location × sowing dates for growth and yield attributes of *Sinapis alba*. It was observed that 15th October sowing at SAWCRI attained 2.25 t ha^{-1} seed yield that was 10.9 % and 24.4 % higher from the optimal dates at NARC and Talagang that accomplished 84.43 %. 91.12 % and 95.76 % more yield from the delayed (15th Dec) sowing at three locations.
Conclusion: Better coordination of soil and climatic conditions with 15th October sowing for growth and development signified the monumental importance of optimal sowing date as the benchmark of superior crop productivity to improve the livelihood of the farmers.

1. Introduction

It is the dire need of the time to understand future imprints of extreme climatic archives on prime agricultural landscape. Particularly in Pakistan, weather vagaries are annoying the situation day by day, particularly for oilseed production (Khan et al., 2021). The scenario is confined to manifold issues like moisture stress, quality seed, pods shattering, insects, diseases with low yield potential of indigenous oilseed crop (Raza, 2021). Pakistan's import spiked to $3.56 billion for the previous fiscal year and only 18 % requirement is met through domestic production (GOP, 2022). Hence, it is obligatory to acquaint a new winter oilseed crop as an alternate choice. The growth habits, wide adaptability and tolerance of *Sinapis alba* to drought-prone environments are well documented (Jankowski et al., 2020). The strong saprophytic self-incompatibility system, better genetic diversity, seed quality and physio-morphic traits for the dry temperate climate (Gennari et al., 2019) are the copious

* Corresponding authors.
E-mail addresses: drmunaf@uaar.edu.pk (A. Manaf), aqayyum@uoh.edu.pk (A. Qayyum).

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agronomic advantages over oilseed rape due to moisture, heat, frost, and pest resistance (Wilczewski et al., 2019). Robust and extensive root system (Jakubus and Bakinowska, 2020), rapid growth with high dry matter production (Wanic et al., 2019) make this multipurpose (Elhakeem et al., 2021), broad leaves plant (Słomka and Wójcik, 2021), highly nutritious livestock feed and attractive for honey bees (Grygier, 2022). Its potential patron to develop important hybrids (Kumari et al., 2020). The Dehiscence zone strength of the *Sinapis alba* pods increases the shattering strength at maturity and combine harvesting is also an added benefit of *Sinapis alba* (Mitrović et al., 2020). These advantages are exclusively pronounced when moisture is limiting, and hence makes *Sinapis alba* an ideal candidate crop for semi-arid climate like Pakistan.

Especially for rainfed areas such as Pothwar plateau, the inherent variability of meteorological conditions, i.e., the intra-seasonal and inter-annual rainfall erraticism, and also the flawed agricultural management decisions often avert crop yield to reach its full potential (Haider and Ullah, 2020). Of all agricultural management decisions, the decision/estimation of optimal sowing date is not a trivial task. Adapting the specific sowing time is much cost-efficient technique to potentially stabilize/intensify crop productivity in rainfed agriculture. Sowing time adjustment mitigates the impact of climate change and is the accurate identification and management for growth and development of a particular species in any cropping system (Cecchin et al., 2021). The optimal sowing date adaptation under varying climatic conditions is obligatory step to ensure sustainability of a specific specie to minimize the contraction of critical developmental segments that will ultimately boosts the proficiency of yield components to favour higher productivity (Attia et al., 2021). Sowing time pedals the source-sink relationship. Peripheral sowing date confines the photosynthetic activity, starch conversion rate, nutrient metabolism, dry matter accretion and eventually the yield. Late sowing restricted the pollen tube formation and hastened the pollen sterility. Similarly, much early sowing might lead to crop disaster and, in turn, delayed sowing reduces valuable growth period and crop yield. In various climatic zones, soil temperature and moisture determines the appropriate sowing time to accomplish target yield of *Sinapis alba* (Harasimowicz-Hermann et al., 2019). Appropriate sowing time avoids fruit shattering, aphids attack, heat stress, diseases attack and ultimately increase seed yield of mustard as compare to early sowing. While late sowing reduces yield due to low moisture and high temperature stress at the reproductive stages (Li et al., 2022; Torrijos et al., 2021). Similarly, apposite sowing date reveals early emergence, timely flowering and physiological maturity due to conducive temperature and moisture (Júnior et al., 2022), while late sowing reduces yield due to low moisture and high temperature stress at the reproductive stage (Page et al., 2021).

Keeping in view the apex importance of *Sinapis alba*, the present study was conducted to evaluate the adaptability, and optimize the best sowing date of *Sinapis alba* in Pothwar to increase the oilseed production that will help to reduce the ever-increasing oilseed export bill of Pakistan.

2. Materials and methods

Field experiments were carried out during Rabi seasons 2017–18 and 2018–19 to evaluate the adaptability of *Sinapis alba* under varying environments at three different locations of Pothwar plateau Viz National Agriculture Research Centre (NARC), Islamabad (latitude 33° 40′ N and longitude 73° 07 ′ E, elevation 504 m) with annual rainfall (>1000 mm). Soil and Water Conservation Research Institute (SAWCRI), Chakwal (latitude 32° 55′ N, longitude 72° 43′ E, elevation 520 m) with annual rainfall of (550–650 mm) and farmer's field at Talagang (latitude 32° 45′ N, longitude 71° 56′ E, elevation 393 m) with annual rainfall of 300–450 mm). Six different sowing dates were evaluated viz. 01-Oct, 15-Oct, 01-Nov, 15-Nov, 01-Dec and 15-Dec. Recommended dose of nitrogen (70 kg ha^{-1}), phosphorus (35 kg ha^{-1}) and potassium (25 kg ha^{-1}) was incorporated in the soil as urea, diammonium phosphate and sulphate of potash at the time of final seedbed preparation. The treatments were organized in a randomized complete block design (RCBD) with four replications. The net plot size was (2.7 m × 5 m). There were six rows in each plot with 45 cm spacing. Treatments were separated from each other by two-meter distance for the admittance of soil and plant sampling. Crop was sown at different locations with manually operated single row hand drill and the seed was used @ 5 kg ha^{-1} Thinning was done in all the treatments after three weeks of sowing to maintain plant to plant distance of 15 cm in each row. Hoeing was carried out at 30 and 60 days after sowing. All the agronomic practices were kept same during the crop lifecycle. The crop was harvested manually at maturity.

2.1. Collection of crop data

Crop data was collected for growth and yield accrediting characteristics of *Sinapis alba.* Days to maturity (DM) were recorded from the date of germination to the date when 75 % crop change its colour and became dry. Plant height (PH) was recorded from ten randomly selected plants from each plot at the time of maturity. Height was measured with measuring tape from soil level to the tip of plant and average was calculated. Number of productive branches (NPB) from ten randomly selected plants from each plot were counted at maturity and the average per plant was worked out. Number of pods per plant (NPP) were counted from ten randomly selected plants of each plot at the time of harvest and their average was worked out. One hundred pods were randomly taken from each plot at maturity to determine the number of Number of seeds per pod (NSP) and counted to work out the average. Three lots of thousand seeds were taken from bulk seed samples of each plot after threshing and weight was recorded by using electrical balance to work out the average thousand seed weight (TSW). Two-meter row length of two central rows was harvested from each plot and plants were sun-dried for few days. Dried samples were weighed to convert biological yield (BY) into t ha^{-1}. Manually harvested plants from two-meter row length of two central rows from each plot were threshed manually after sun drying. The obtained seeds were weighed to convert seed yield (SY) into t ha^{-1}.

2.2. Collection of soil data

Composite soil samples of each replication were collected for moisture content from 0 to 15 cm and 15–30 cm depths before sowing and after regular intervals of 15 days till harvest of the crop at all the three locations during both years to work out the average moisture content (0–30 cm) (Fig. 1). Moisture content were determined by Gravimeter method, soil pH was measured by pH meter, electrical conductivity by the conductivity meter, phosphorus was recorded by Spectrophotometer, extractable K by flame photometer as mention by (Westerman, 1990). Organic matter and Nitrate-N were worked as off (Keeney and Nelson, 1982). Physico-chemical properties of the experimental sites are given in Table 1.

2.3. Collection of climatic data

Pakistan Meteorological Department, Islamabad provided the weather data (rainfall, temperature and relative humidity) of the

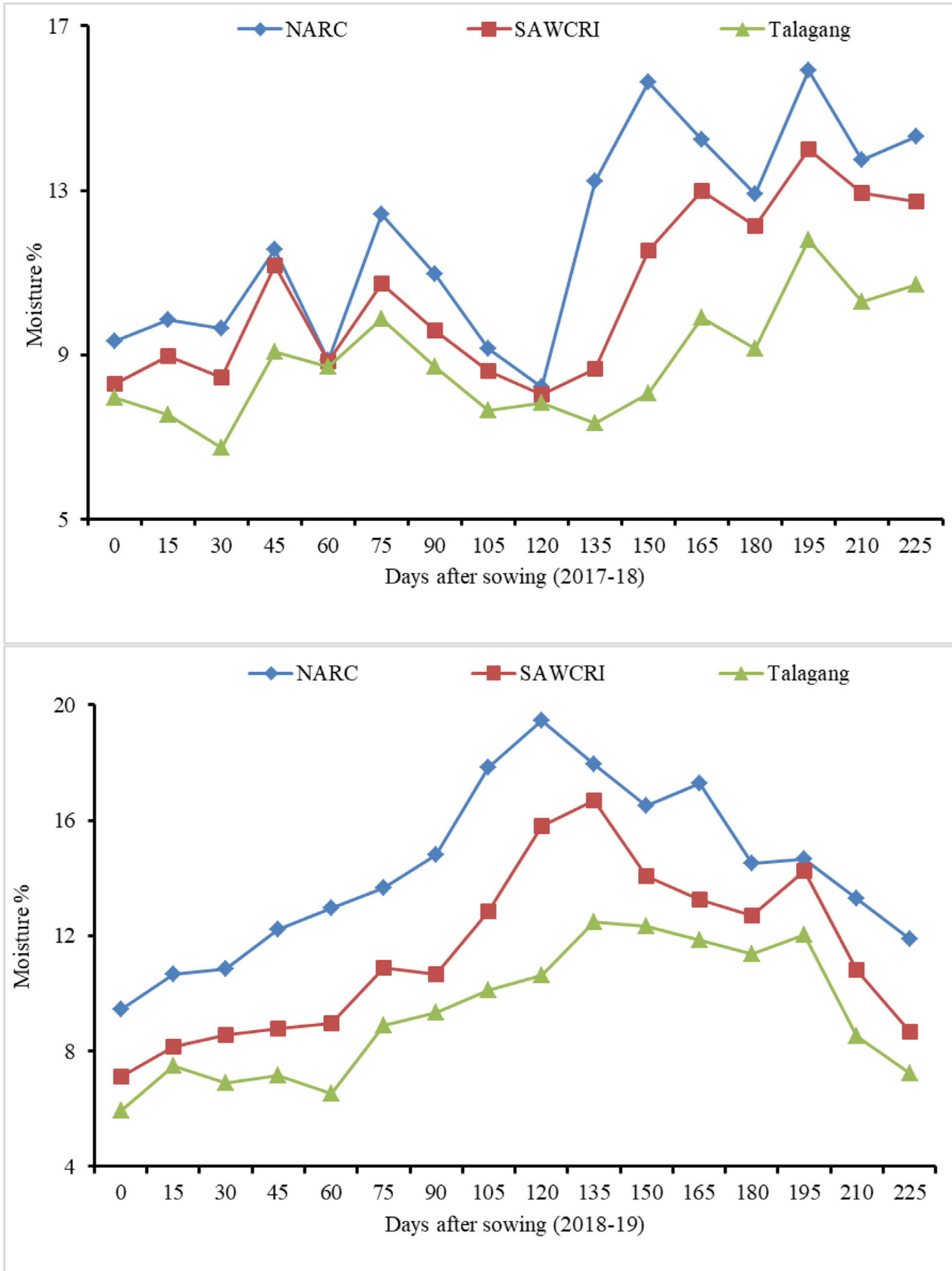

Fig. 1. Soil moisture (%) at 0–30 cm soil depth across three locations (2017–18 and 2018–19).

experimental sites during both years from their nearby observatories (Figs. 2 and 3).

2.4. Statistical analysis

A general linear model for analysis of variance (ANOVA) was adopted by (Steel and Torrie, 1980) using a computer program (Statistics 8.1). The Randomized Complete Block Design (RCBD, 3-factorial) was applied to determine the significance level of key experimental factors (sowing dates, locations and years) and their possible interactions. Besides this, the least significance test (LSD) was applied with a probability level of 5 % to identify significant variation between the means. Moreover, with the help of Pearson's correlation, the linear association between the agronomic traits was determined and Statistic 8.1 helped to computed correlation coefficient (r) values (Sedgwick, 2012), and p-values were computed to classify numerous agronomic traits of *Sinapis alba* in response to the treatment interactions i.e. sowing date × location × year.

3. Results

3.1. Influence of sowing dates

Sowing dates pooled over years and locations, revealed statistically significant differences ($p \leq 0.05$) among mean values of all the observed growth and yield characteristics Table 2. 1st October sowing gained statistically maximum DM (196.6) and PH (224.5 cm). While, 15th October sowing logged statistically maximum mean values for NSP (1845), and TSW (4.87). However, the

Table 1
Physico-chemical properties of the experimental sites.

	NARC				SAWCRI				Talagang			
	2017–18		2018–19		2017–18		2018–19		2017–18		2018–19	
Depth	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30	0–15	15–30
Texture	SCL	SCL	SCL	SCL	SL	SL	SL	SL	SL	SL	SL	SL
Sand (%)	72.3	70.3	70.2	68.1	80.6	78.1	78.1	75.5	77.3	73.5	76.6	75.7
Silt (%)	17.4	18.6	18.1	19.3	13.2	14.8	14.3	16.2	14.1	17.4	14.5	15.1
Clay (%)	10.3	11.1	11.7	12.6	6.2	7.1	7.6	8.3	8.6	9.1	8.9	9.2
Ph	7.8	7.6	7.9	7.7	7.93	7.8	7.93	7.7	8	7.9	7.8	7.6
EC (dsm^{-1})	0.87	0.86	0.92	0.89	0.75	0.63	0.75	0.63	0.9	0.87	0.93	0.89
O.M (%)	0.82	0.79	0.81	0.74	0.61	0.54	0.62	0.53	0.67	0.63	0.68	0.61
Aval. P (ppm)	7.8	6.7	7.5	6.9	5.3	4.9	5.5	5.1	6.1	5.4	6.2	5.6
Aval. K (ppm)	241	198	243	198	223	214	219	205	184	162	187	174
NO_3.N (ppm)	6.3	5.8	6.4	5.9	6.1	5.7	6.2	5.6	5.9	5.1	5.8	5.4
B.D (g cm^{-3})	1.84	1.92	1.89	1.93	1.67	1.81	1.73	1.84	1.61	1.74	1.63	1.75
Porosity (%)	46.7	45.9	47.1	46.5	42.1	41.7	41.7	40.9	43.2	42.6	43.6	42.8
Saturation (%)	36.3	37.1	37.2	38.1	34.5	35.2	33.9	34.2	33.9	34.1	34.1	34.5

SL = Sandy loam, EC = Electrical conductivity, O.M = Organic matter, B.D = Bulk density.

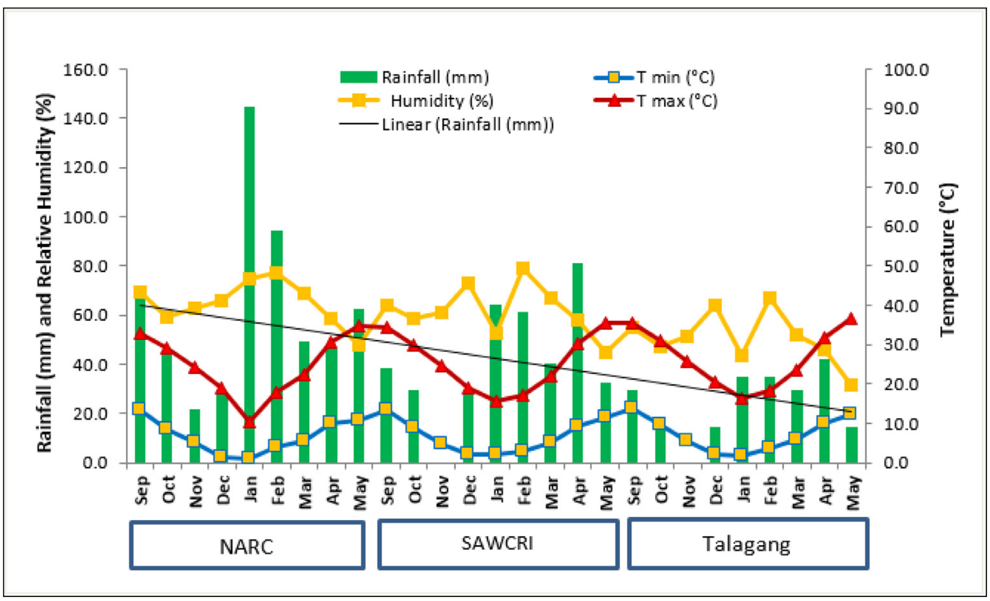

Fig. 2. Weather data of the experimental sites during 2017–18.

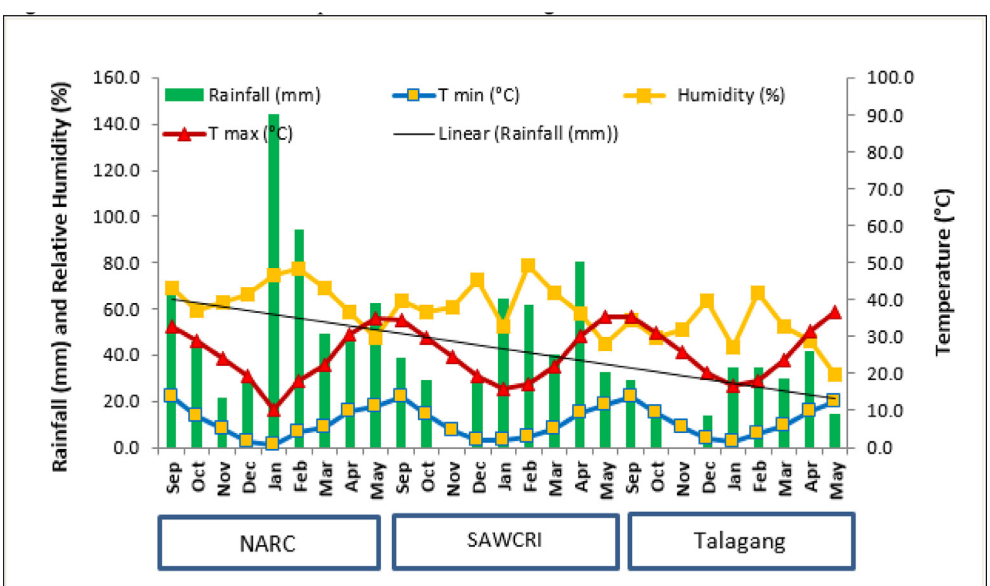

Fig. 3. Weather data of the experimental sites during 2018–19.

highest mean values for NPB, NPP, BY (10.912 t ha^{-1}) and SY (1.955 t ha^{-1}) for 15th October sown crop were statistically parallel with 1st October sowing. On the other hand, *Sinapis alba* sowing on 15th December produced lowest mean values for all the observed attributes of growth and yield.

3.2. Influence of locations

Among locations, sowing of *Sinapis alba* exhibited differential response ($p \leq 0.05$) for the mean values of all the observed traits (Table 2). NARC grabbed maximum DM (179.6) to accomplished

Table 2
Influence of years, locations and sowing dates on the growth and yield related traits of *Sinapis alba*.

	DM	PH	NPB	NPP	NSP	TSW	BY	SY
Years	**	NS	**	**	NS	**	**	**
2017–18	167.9b	144.6a	18.3b	951.2b	3.5a	4.32b	7276.2b	1032.6b
2018–19	173.9a	147.5a	19.7a	1033.3a	3.4a	4.47a	7779.7a	1144.9a
SE±	0.19	2.28	0.32	17.39	0.05	0.01	130.48	20.11
Locations	**	**	**	**	**	**	**	**
NARC	179.6a	152.5a	20.3a	1063.2a	3.6a	4.59a	7960.6a	1159.8a
SAWCRI	170.9b	157.5a	20.8a	1054.3a	3.6a	4.43b	8062a	1191.5a
Talagang	162.3c	128.1b	15.9b	859.3b	3.2b	4.18c	6561.2b	914.9b
SE±	0.23	2.79	0.4	21.31	0.06	0.01	159.8	24.63
Sowing dates	**	**	**	**	**	**	**	**
01-Oct	196.6a	224.5a	33.2a	1730.8b	4.9a	4.8b	10799a	1870.7a
15-Oct	188.6b	208.2b	31.6a	1845.3a	5a	4.87a	10912a	1955.4a
01-Nov	177.1c	163c	20.9b	1091.2c	3.9b	4.48c	8783b	1277.3b
15-Nov	165.3d	124.7d	14c	691.3d	3.1c	4.29d	6958c	782.9c
01-Dec	154.3e	95.1e	8.9d	387.5e	2.4d	4.07e	4767d	432.7d
15-Dec	143.7f	60.7f	5.4e	207.6f	1.7e	3.89f	2949e	213.2e
SE±	0.33	3.95	0.56	30.13	0.09	0.02	225.9	34.83

*Significant at $p \leq 0.05$, **Significant at $p \leq 0.01$, [NS]Non-significant. The values in columns having different small letters are significantly different at $p \leq 0.05$.

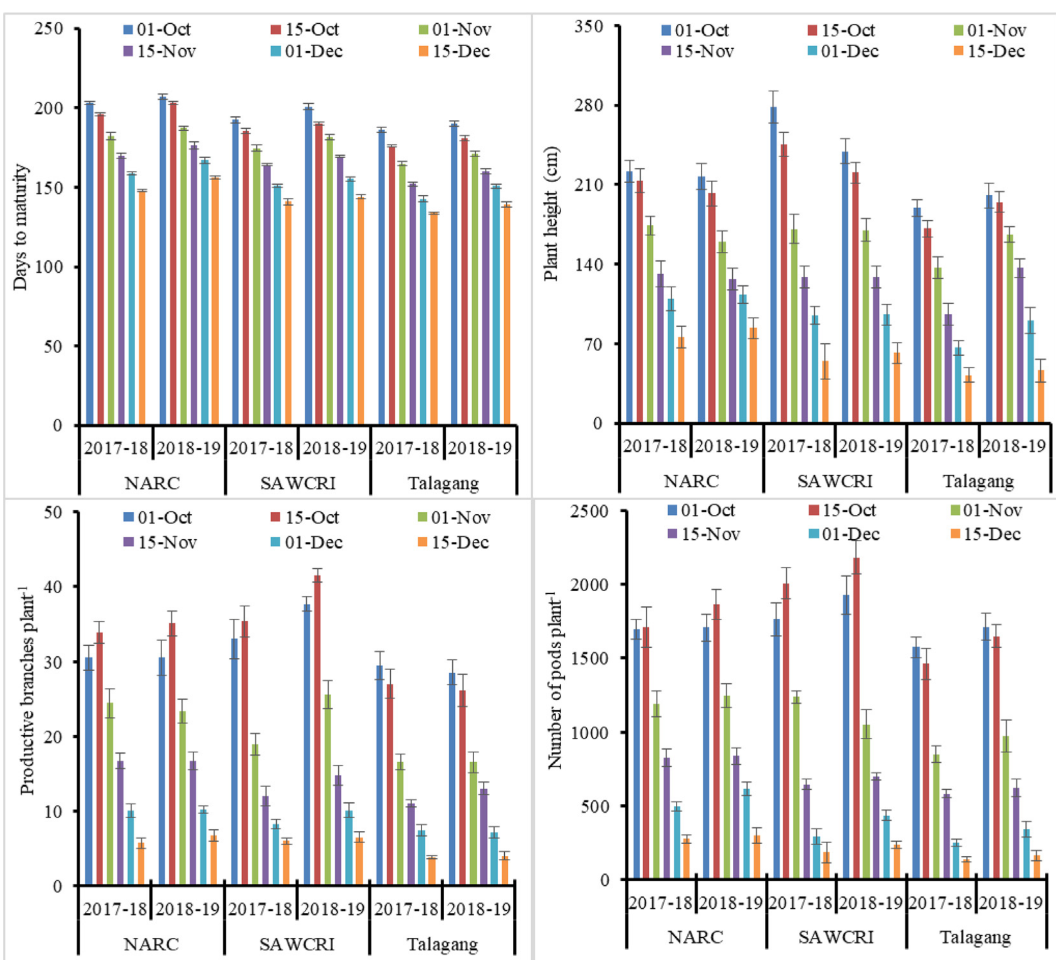

Fig. 4. Influence of sowing dates on growth traits of *Sinapis alba* during 2017–18 and 2018–19.

statistically maximum TSW (4.59 g). Whereas maximum NPB (20.8), BY (8.06 t ha^{-1}), and SY (1.19 t ha^{-1}) were statistically not different from SAWCRI. While, Talagang attained statistically lowest location means i.e., DM (162.3), NPB (19.5), NPP, (859), NSP (3.2), TSW (4.18 g), BY (6.56 t ha^{-1}) and SY (9.15 t ha^{-1}).

3.3. Influence of years

During both years, sowing dates revealed statistically significant differences ($p \leq 0.05$) among mean values (Table 2) for DM, NPB, NPP, TSW, BY and finally the SY of *Sinapis alba*, except PH and NSP, where both years reckoned non-significant differences. However, mean DM (173.9), NPB (19.7), NPP (1033), TSW (4.47 g), BY (7.78 t ha^{-1}) and SY (1.14 t ha^{-1}) revealed statistically superior results during 2018–19.

3.4. Interactive influence of sowing dates, years and locations

The three-way interaction of years, locations and sowing dates revealed significant differences ($p \leq 0.05$) and bars indicate standard error (±SE) of mean (n = 3) for all the parameters of growth and yield of *Sinapis alba* during both years at three locations (Figs. 4 and 5). The data (Table 2) revealed that 1st October sowing at NARC gained maximum DM (207.3) during 2018–19, while 15th December sowing at Talagang acquired minimum DM (133.7) during 2017–18. Crop sown on 1st October at SAWCRI nurtured the plants for maximum PH (278.3 cm) during 2017–18, and 15th December sowing at Talagang developed the plants for minimum PH (42.4 cm) during 2017–18. 15th October sowing exhibited maximum NPB (41.5) at SAWCRI during 2018–19, while 15th December sown crop established minimum NPB (3.8) during 2017–18. The maximum NPP (2184) were chronicled for 15th October during 2018–19 at SAWCRI. Sowing on 15th December at Talagang nurtured minimum NPP (138).

1st October sowing during both the year at all the locations revealed statistically parallel results with maximum NSP (5.3) amassed by 15th October at SAWCRI during 2017–18, which showed non-significant differences for 2018–19 at the same location and with NARC during both years. While, minimum NSP (1.5) developed by 15th December sowing at Talagang during 2017–18 reckoned statistically similar results during second year. The divergent response was observed among sowing dates for TSW at three locations during both the years. At SAWCRI maximum TSW (5.14 g) gained by 15th October sowing during 2018–19 year exhibited statistical equivalence with first year, and as well as with 1st October during second year at this location. Whereas, the minimum TSW (3.6 g) gained at Talagang during 2017–18 showed statistically parallel results when the crop was sown on 15th December during both years. Rest of the interactions narrated almost different results for this trait. It is ostensible from the

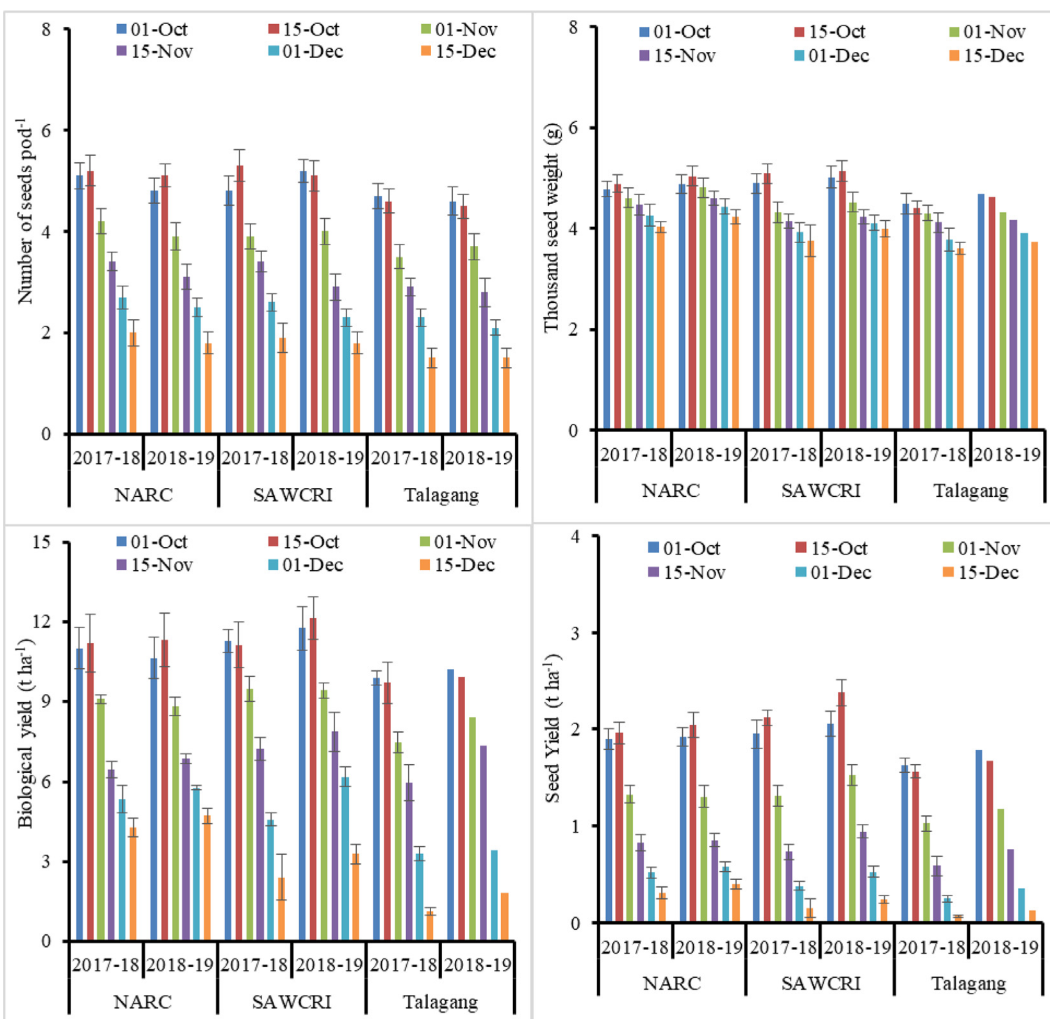

Fig. 5. Influence of sowing dates on yield and yield traits of *Sinapis alba* during 2017–18 and 2018–19.

Table 3
Correlation coefficients among the agronomic traits of *Sinapis alba.*

Traits	DM	PH	NPB	NPP	NSP	TSW	BY
PH	0.9113*						
NPB	0.9143*	0.9235**	0.9266**				
NPP	0.9089*	0.947**	0.9668**				
NSP	0.9016*	0.9546**	0.9382**	0.9579**			
TSW	0.9284*	0.9127*	0.9153*	0.9254**	0.9012*		
BY	0.9159*	0.948**	0.9146*	0.9291**	0.9412**	0.9033*	
SY	0.9268**	0.9658**	0.9654**	0.9852**	0.9687**	0.927**	0.955**

*Significant at $p \leq 0.05$, ** Significant at $p \leq 0.01$, ns = non-significant.

(Fig. 4) that maximum BY (12.14 t ha^{-1}) recorded at SAWCRI for 15th October during 2018–19 showed statistical similarity with first year at the same location, and along with 1st October & 15th October sowing at NARC during both years. The minimum BY (1.14 t ha^{-1}) recorded at Talagang for 15th December during 2017–18 reckoned nonsignificant differences with the second year. It is obvious from the (Fig. 5) that 15th October sowing at SAWCRI during 2018–19 logged statistically maximum SY (2.38 t ha^{-1}) from all the sowing dates × years × locations, while 15th December sowing at Talagang exhibited minimum SY (0.068 t ha^{-1}) during 2017–18. Other means exhibited varying degrees of differences.

3.5. Correlations among agronomic traits

Seed yield exhibited significant and positive correlation with vegetative units i.e. DM, PH, NPB and as well with yield attributes i.e. NPP, NSP, TSW and BY (Table 3) in the current study. Optimal sowing time was the most probable reason of strongly positive correlation of vegetative units to enhances the seed yield of oil seed brassica (Butkevičienė et al., 2021; Mitrović et al., 2020). Our findings are also on the similar tract that appropriate sowing environment enhanced Physio-Morphic correlation among yield and yield components (Radić et al., 2021). Sowing time regulated the strength of relationship among yield attributes of oilseed brassica (Jadhav and Jadhav, 2021).

4. Discussion

The experiment was performed under varying environments. The wide variation in DM among sowing dates was due to variation in pluvio-thermal conditions for each sowing date among locations during both years (Table 2). More precipitation, cool days, suitable humidity, low temperature and relatively more clay content at NARC, significantly prolonged the growth and development period that protracted DM (Fig. 4) for all sowing dates as compared to SAWCRI and Talagang during both the years. Minimum DM for all the sowing dates at Talagang was due to relatively low rainfall and high temperature at particular site (Figs. 1 and 3). Relatively low moisture and cold stress at Talagang for 15th December sowing reduced the vegetative period and relatively high temperature and moisture deficit near reproductive period increased evapotranspiration hastened the maturity. Optimum sowing date, productive environmental conditions and balanced source-sink ratio during the whole crop cycle increased the days to maturity of mustard (Liu et al., 2021), and delayed sowing as well as unfavourable pluvio-thermal conditions accelerated the generative phase of *Sinapis alba* (Harasimowicz-Hermann et al., 2017).

1st October sowing attained the maximum PH during both the years (Table 1). Early growth stage escaped from the frost in comparison to delayed sowing. The appropriate temperature and suitable moisture at early phenological phases accelerated the plant growth and development. *Sinapis alba* sowing on 15th December was more vulnerable to moisture and weather desolations. During both the years, 1st October sowing at SAWCRI accomplished optimal temperature, highly suitable soil and plant environment exploited maximum photo-assimilates which significantly escalate the plant height (Fig. 4). Short plant stature at Talagang might be due to low organic matter, poor nutrient and low soil moisture which hampered all plant functions, thus reduced dry matter accumulation, and confined the growth period which produced the shortest plants. Our results are in the same line that optimal sowing dates fostered the tallest plant as compare to delayed sowing (Jadhav and Jadhav, 2021).

The crop sown earlier on 1st & 15th October during both the year received highest total precipitation, solar radiations and soil nourishment from emergence to maturity which promoted better resources utilization for maximum photo assimilation that increase in the NPB (Fig. 4). Frost at the early phenophases, and relatively high temperature at lateral stages constricted the crop cycle of November and December sowing due to less assimilate production. SAWCRI and NARC attained maximum NPB among locations during October sowing. The minimum NPB at Talagang during 15th December sowing was due to destitute moisture, low humidity (Figs. 2 and 3) and unfavourable temperature that hampered photosynthetic ability to diminished growth and development process. Delay sowing led to poor formation of individual vegetative traits especially NPB of oil seed brassica (Kuzmanović et al., 2021; Shafighi et al., 2021).

Adequate vegetative development due to optimal growth condition during phenological phases produced statistically maximum number of floral buds that probably developed more pods (Fig. 5) for 15th October sowing at SAWCRI during 2018–19. Whereas, poor assimilate capacity due to low rainfall with high-temperature environment at Talagang reduced NPP during both the years. Suitable soil and plant environment with suitable rainfall promoted abundant flowering which boosted the development of all yield attributes (Boote et al., 2021). Late sowing and adverse climate during flowering, fertilization, and silique development reduced NPP of mustard (Yu et al., 2020).

October sowing particularly at NARC and SAWCRI during both the years gained maximum NSP (Fig. 5). Sufficient moisture, suitable temperature synchronized with abundant flowering due to highest source-sink ratio increased production of assimilates. Late sowing of *Sinapis alba* in December at all the locations during both years confronted with aberrant soil moisture status and harsh climatic conditions restricted pollen tube formation and inferior seed set. similar findings that optimal sowing (Li et al., 2022), and suitable climatic condition during growth period with better phenological development increased the number of seeds per pod in *Sinapis alba* (Jankowski et al., 2020). Better siliqua development on the stem ensured highest seed pod^{-1} in *Sinapis alba* (Zając et al., 2011). Climatic variations like solar radiations, evapotranspiration and daily mean temperature significantly influenced yield formation stages in brassica (Pullens et al., 2021).

Suitable atmosphere at early vegetative period, optimal day length accelerated the assimilate production due to delayed senescence that increased seed set and ultimately TSW for 15th October sowing at SAWCRI (Fig. 5). Deprived germination in December particularly at Talagang, and wilting of leaves at early seedling due to low moisture (Figs. 1-4), high temperature at pollination and fertilization aborted reproductive organs that produced immature and fuzzy seeds during both years. Optimal sowing time significantly improved the yield attributing traits of rapeseed, and yield variability at the time of yield formation stages was due to variations in agro-climatic index like solar radiations and evapotranspiration (Tribouillois et al., 2016). Sufficient rainfall at flowering was the foremost reason for higher seed weight, and delayed sowing as well as poor hydrothermal conditions reduced the photosynthetic activity and sink capacity of reproductive organs which reduced TSW of *Sinapis alba* (Harasimowicz-Hermann et al., 2019). Drastic changes in average biological yield due to soil ((Table 1) and climatic variability among locations structured the overall performance of the sowing dates during both years. During October sowing no precipitation deficit (Fig. 1), better soil health, suitable temperature, considerable length of the all growth phases, superior phenological development, high source-sink ratio increased the biological yield at SAWCRI and NARC as compared to Talagang during both the years (Fig. 5). December sowing conceded poor germination due to the chilling effect, moisture and heat stress at developmental stages that produced less assimilates. Low rainfall environment at Talagang reduced biological yield in compared to SAWCRI and NARC. suitable temperature, sufficient annual rainfall during vegetative development increased above-ground biomass and yield of *Sinapis alba* (Biabani et al., 2021).

Final SY of a crop is the ultimate product of physiological and morphological development during its life cycle. The edaphic and climatic variability among the locations inclined the overall performance of the sowing dates during both years (Table 1; Figs. 1-3). 15th October sowing at SAWCRI produced maximum SY because vegetative and developmental stages confronted no moisture, cold and heat stress during the length of each phenophases, particularly during 2018–19 (Fig. 5). Short vegetative and confined generative period accelerated the senescence which forced the maturity in delayed sowing that reduced the SY at all the locations during both years. Relatively low SY was attributed to inadequate availability of solar radiations for photosynthetic activities due to frequent cloudy days at NARC during January and February and high temperature at pre and post anthesis duration at Talagang. Our findings that appropriate sowing time and suitable pluvio-thermal conditions at individual growth stages determined the yield potential of *Sinapis alba* and high rainfall events from flower initiation to maturity increased hydrothermal coefficient that reduced seed yield due to poor pollination were supported by (Pradhan et al., 2014: Wilczewski et al., 2019). Delayed sowing for 85 days from the optimum date reduced (79 %) seed yield of *Sinapis alba* (Harasimowicz-Hermann et al., 2019). Cool temperature, adequate and well-distributed precipitation over the important growth stages improved strong relationship among productive components (Rajković et al., 2022).

5. Conclusions

It could be concluded from the current study that the productivity of *Sinapis alba* was significantly influenced by the soil and environmental conditions of different ecological locations. Among all the locations, NARC being a high rainfall site and Talagang as less fertile, low rainfall and high-temperature area is modestly pertinent for *Sinapis alba* cultivation. Whereas, the optimal temperature and rainfall environment at SAWCRI is the most suitable husbandry for *Sinapis alba*. Observance of the current study subsequently assents the following recommendations for the farming community to uplift their livelihood. *Sinapis alba* could be successfully cultivated in all the ecological areas of the Pothwar (high, medium and low rainfall); *Sinapis alba* is surely a new alternate choice to diversify the prevailing cropping system and 15-October is the optimum sowing time for *Sinapis alba* to avoid high temperature at sowing and maturity for best growth and maximum seed yield in the prevailing climate change scenario.

Author contributions

A.M. conceived the idea. G.M. conducted the experiments. A.S., A.H.B. and A.M.E. collected the literature review. F.U.H. and A.K. provided technical expertise to strengthen the basic idea. A.Q., A. S. and C.J.L. helped in statistical analysis. A.M. proofread and provided intellectual guidance. All authors read the first draft, helped in revision and approved the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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