

SOWING TIME AND CULTIVARS SELECTION MATTERS TO ENHANCE SOYBEAN PRODUCTIVITY UNDER CONTRASTING AGRO-ECOLOGICAL ZONES IN PAKISTAN

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ABSTRACT

Soybean (*Glycine max* (L.) Merr.), hailed as the "golden bean," is a globally significant crop valued for its high nutritional value, soil-enriching nitrogen fixation capacity, and wide-ranging applications in food, feed, and industry. Despite its higher yield potential, soybean cultivation in Pakistan remains limited, primarily due to erratic climatic conditions, suboptimal agronomic farming practices, and restricted access to quality seed. This study aimed to evaluate the interactive effects of planting time, cultivar selection, and climatic conditions on soybean growth and yield under contrasting agro-ecological zones. Field experiments were carried out over two consecutive seasons: 2021 and 2022 under rainfed conditions in Chakwal and irrigated conditions in Swat. Two soybean cultivars, NARC-2 and NARC-21 were sown on June 5, June 25, and July 15 using a randomized complete block design with a split plot arrangement. Early planting on 5 June conferred a significant advantage, as delaying sowing on 15 July resulted in substantial reductions in physiological and yield parameters, including a 51.01% decline in leaf area index (LAIX), a 56.76% decrease in total dry matter (TDM), and a 56.83% reduction in grain yield (GY). NARC-21 consistently outperformed NARC-2, especially at the Swat location, where adequate irrigation and higher solar radiation contributed to improved physiological development and yield. Early sowing (5 June) of cultivar NARC-21 under irrigated conditions exhibited >50% higher yield than late sowing. Conversely, delayed planting shortened the growing season by 16.7%, resulting in limited biomass accumulation and grain yield. Climatic analysis revealed strong positive correlations between soybean performance, total solar radiation, and optimal temperature regimes, confirming the crop's sensitivity to planting time and environmental cues. Our results indicate that NARC-21 consistently outperformed NARC-2 across all sowing dates, with higher yields recorded at both locations. Overall, yield was greater at Swat than Chakwal, highlighting the importance of cultivar adaptability and favorable agro-environmental conditions. These findings underscore the need for climate-smart cultivar selection and policy support to promote early planting strategies across Pakistan's agro-ecological zones.

Keywords: Planting time, agro-ecological zones, rainfed agriculture, irrigated conditions, phenology, climate variability

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INTRODUCTION

Soybean (*Glycine max* (L.) Merr.), domesticated approximately 3,000 years ago in East Asia, is globally recognized for its agronomic, nutritional, and industrial value (Lee *et al.*, 2011; Kumari *et al.*, 2023). As a leading oilseed crop, it serves as a vital source of vegetable oil, protein meal, and raw material for the biofuel and processing industries (Ali *et al.*, 2020). Soybean enhances sustainable agriculture by fixing atmospheric nitrogen and improving soil fertility (Yano and Saeki, 2023). The major soybean-producing countries include the United States, Brazil, Argentina, China, India, and Paraguay, with the U.S. and Brazil contributing 28% and 40% of

global output (Voora *et al.*, 2020; USDA, 2023 Holodna and Hrytsiuk, 2024).

Pakistan introduced soybean in the 1960s in Sindh and Khyber Pakhtunkhwa (Khurshid *et al.*, 2017). Its cultivation declined significantly by the late 1990s, with the area dropping from 6,200 ha to just 60 ha and production declining sharply from 8,100 tons to 50 tons between 1997 and 1998 (Khan *et al.*, 2024). This decline resulted from limited breeding efforts, lack of regionally adapted cultivars, and poor integration into existing cropping systems (Arshad *et al.*, 2006). Consequently, Pakistan remains heavily reliant on oilseed imports to meet domestic demand. In 2023–24 (July–March), edible oil imports totaled 2.7 million tons, valued at Rs 794 billion (US\$2.809 billion), while local production stood

at only 0.471 million tons (Ministry of Finance, 2024). This dependence strains the economy and limits the adoption of legume-based rotations that could otherwise benefit soil health (Khan and Khan, 2018). Moreover, the lack of genetically diverse, locally adapted germplasm continues to constrain the expansion of production (Ullah *et al.*, 2021). Soybean production in Pakistan also faces agro-climatic challenges, including erratic rainfall, temperature extremes, and recurrent droughts and floods, which adversely affect yield (Fatima and Jan, 2023; Hamed, 2025). Given the crop's sensitivity to genotype \times environment \times management interactions, region-specific strategies are essential for optimizing productivity (Ishibashi *et al.*, 2003; Morris *et al.*, 2021; Nataraj *et al.*, 2024).

The sowing date is a critical factor influencing soybean yield, as it governs phenological development, crop-environment interactions, and the availability of resources during key growth stages (Serafin-Andrzejewska *et al.*, 2024). Appropriate sowing timing optimizes vegetative and reproductive phases, ensuring effective pod set, canopy closure, and light interception, all of which contribute to maximizing yield potential (Fordoński *et al.*, 2023; Hussain *et al.*, 2025). Moreover, adjusting sowing dates serves as an effective strategy to adapt soybean cultivation to changing climatic conditions (Minoli *et al.*, 2022). Timely sowing aligns crop development with favourable temperature regimes and adequate solar radiation, enhancing photosynthetic efficiency and biomass accumulation (Hussain *et al.*, 2012a, b; Patel *et al.*, 2019). In soybean, sowing time also modulates photoperiod sensitivity and significantly affects grain yield (Bossolani *et al.*, 2022). However, most existing studies have investigated these factors in isolation, and comprehensive studies examining their combined effects across diverse agro-ecological zones remain limited.

The study focuses on Pakistan's contrasting agroecological zones represented by Chakwal (rainfed, semi-arid) and Swat (irrigated, temperate) to evaluate soybean adaptability under divergent growing conditions. Chakwal is a rainfed system, where most of the farmland follows wheat-dominant rotations that could benefit from legume integration (Ramesh *et al.*, 2017; Goheer *et al.*, 2023). Conversely, Swat's irrigated conditions establish productivity benchmarks while assessing the yield and phenology. This dual-site approach enables comprehensive analysis of sowing date \times location \times cultivar interactions across Pakistan's major agricultural systems, addressing both current production constraints and future climate adaptation needs.

The objective of this study is to evaluate the effect of sowing dates, cultivar selection (NARC-2 vs. NARC-21), and agroecological conditions (rainfed-Chakwal vs. irrigated-Swat) on soybean phenology and yield formation over two growing seasons (2021–2022).

Furthermore, the study investigated the influence of seasonal weather parameters, particularly solar radiation and temperature, on soybean performance, aiming to identify correlations between environmental conditions and crop outcomes. Through this integrative approach, the study seeks to inform climate-resilient and location-specific soybean production strategies in Pakistan

MATERIALS AND METHODS

Experimental site: The experiments were conducted during the 2021–2022 growing seasons (June and July) at two contrasting locations in Pakistan: a rainfed site at the Agricultural Research Farm in Chakwal, Punjab (33.1166°N, 73.0111°E) managed by PMAS Arid Agriculture University Rawalpindi, and an irrigated site at the Agricultural Research Institute in Mingora, Swat (34°46'47"N, 72°19'47"E). The study employed a randomized complete block design (RCBD) with split plot arrangement and three replications. Main plots comprised planting dates (5 June, 25 June, and 15 July). Whereas sub-plots included two soybean cultivars (NARC-2 and NARC-21). Soybean were sown at a seed rate of 100 kg/ha, with rows spaced 45 cm apart and individual plants spaced 5 cm within rows. At sowing, fertilizer was applied at the following rates: nitrogen (urea) at 25 kg/ha, phosphorus (Diammonium phosphate) at 60 kg/ha, and potassium (potassium sulphate) at 50 kg/ha to promote optimal growth.

Soil and weather data: Soil physicochemical properties were assessed before planting, as shown in Table 1. Soil samples were collected from the surface, 0-60 cm, and 60-90 cm. Composite samples were prepared by mixing soil from each depth, then air-dried, lightly crushed, and passed through a 2 mm stainless steel sieve for laboratory analysis. Weather data, including daily maximum and minimum temperatures, rainfall, and solar radiation, were recorded at meteorological stations near the experimental sites in Chakwal and Swat, respectively, throughout both growing seasons.

Crop data: Phenological data, including days to anthesis, pod formation, and days to maturity, were recorded by daily observation. Ten plants were randomly selected and tagged in each treatment, and average values from these plants were used in the analysis. Days to flowering (DTF) were noted when 50% of plants showed the first open flower; days to pod formation (DTP) when 50% of plants developed visible pods; and days to maturity (DTM) when 90% of pods reached physiological maturity. The number of days from sowing to each stage was calculated accordingly.

Leaf Area Index (LAI) per plant was measured by harvesting all leaves from individual plants. Leaf area was recorded using a LI-COR LI-3100C Leaf Area Meter (Lincoln, Nebraska, USA). Total leaf area per plant was

divided by the ground area occupied by the plant to calculate LAI using the following equation (Eqn.1).

$$\text{LAI} = \text{Total Leaf Area (m}^2\text{)} / \text{Ground Area (m}^2\text{)} \dots (\text{Eqn.1})$$

At physiological maturity, plants were harvested at ground level. Samples were oven-dried at 70°C until a constant weight was obtained. Total dry matter (TDM) was recorded per plant and converted into kilograms per hectare for field-level estimation. Using an electronic balance, a thousand seed weight (TSW) was determined by randomly counting and weighing 1000 fully mature, dry seeds. Results were expressed in grams (g). Grain

yield was determined by harvesting plants, followed by manual threshing, cleaning, and weighing the grains.

Statistical analysis: Analysis of variance (ANOVA) was conducted to assess the effects of location, sowing date, cultivar, and their interactions. Where ANOVA indicated significant differences ($p \leq 0.05$), Tukey's honest significant difference (HSD) test was applied for pairwise mean comparisons ($p \leq 0.05$). All statistical analyses were performed using R Studio software (R version 4.3.2).

Table 1: Physicochemical attributes of soil at experimental locations

Soil characteristics	Swat			Chakwal		
	Surface	30cm	90cm	Surface	30cm	90cm
Soil depth	Surface	30cm	90cm	Surface	30cm	90cm
Soil texture	Loam	Loam	Loam	SCL	SCL	SCL
pH (1:2.5) Value	6.7	6.1	6.4	8.1	8.1	8.1
EC (1:2.5) dS/m	0.14	0.1	0.11	0.18	0.14	0.1
Organic Matter (%)	0.74	0.8	0.67	0.43	0.35	0.29
Nitrogen (%)	0.046	0.05	0.042	0.027	0.02	0.018
Av. P (ppm)	17	22	23	9	4	4
Ex. K (ppm)	98	94	86	112	110	110

Abbreviations: SCL = Sandy Clay Loam, EC = Electrical Conductivity, Av. P = Available Phosphorus, Ex. K = Exchangeable Potassium, ppm = parts per million

RESULTS

Weather conditions during the study period: The year 2021 was slightly warmer than 2022 at both experimental locations, and the total rainfall during the soybean growing season was higher in 2022. The maximum temperatures (Tmax) in Chakwal and Swat were recorded as 45.2°C on 7 June 2022 and 32°C on 28 June 2022, respectively. The highest daily precipitation was recorded as 131.2 mm day⁻¹ on 29 July 2022, 63.3mm day⁻¹ on 12 July 2022 at the exact location. In contrast, the minimum temperature (Tmin) was recorded as 5.4°C on 7 October 2022, at the experimental site in Swat. Temperature, solar radiation, and rainfall data patterns during the growing season are presented in Figure 1.

Effect of sowing time and location on phenological attributes: The results demonstrated a statistically significant effect ($p \leq 0.01$) of location, sowing date, and cultivar on crop's phenological development (ANOVA table S1). The cultivation of soybeans in Swat demonstrated extended phenological durations as compared to Chakwal. As is evident from the data in Table 2, experimental plants in Chakwal took 17% lesser number of days (94.46 days) to maturity (DTM) as compared to those in Swat (114.21 days). Similarly, delayed sowing resulted in a marked reduction across phenological stages. As observed, early sowing (SD1, 5

June), took a maximum time of 114.31 days to mature (DTM), whereas late sowing (SD3, 15 July) took 17% lesser number of days to reach maturity. Similarly, other phenological traits of late sowing soybean plants such as days to pod formation (DTP) and days to flowering (DTF) took 20% and 22% lesser time, respectively, as compared to early sowing (Table 2). Between cultivars, NARC-2 showed a longer growth duration than NARC-21 (Table 2).

The interactive effects of location and year significantly influenced the days to flowering (DTF), days to pod formation (DTP), and days to maturity (DTM) ($p \leq 0.01$; ANOVA table S1; Figure 2a). Experimental plants maintained under irrigated conditions (Swat) possessed an elongated period for flowering as compared to those cultivated under rainfed conditions (Chakwal) during both cropping seasons. Additionally, within each location, the mean days to flowering were generally greater during the first cropping season (2021) than in 2022, suggesting a marginal reduction in flowering time in the subsequent year. Although a gradual decrease in flowering duration was observed during 2022 as compared to 2021, flowering under irrigated conditions (Swat) was consistently delayed as compared to Chakwal. A Similar trend was observed for pod formation and maturity periods during both study years (Figure 2 b, c).

Table 2: Effects of location, sowing date, cultivar, and year on phenology and yield components of soybean

Parameters	SWAT	CHAK	SD1 (5 June)	SD2 (25 June)	SD3 (15 July)	NARC-2	NARC-21
DTF	42.75 ^a	36.08 ^b	44.37 ^a	39.43 ^b	34.43 ^c	41.41 ^a	37.41 ^b
DTP	53.29 ^a	45.54 ^b	55.12 ^a	49.18 ^b	43.93 ^c	50.54 ^a	48.29 ^b
DTM	114.21 ^a	94.46 ^b	114.31 ^a	103.69 ^b	95.00 ^c	107.04 ^a	101.62 ^b
LAIX	3.05 ^a	2.18 ^b	3.47 ^a	2.68 ^b	1.70 ^c	2.41 ^a	2.82 ^b
TSW	168.57 ^a	143.82 ^b	168.29 ^a	157.85 ^{ab}	142.44 ^b	NA	NA
TDM	3077.7 ^a	2039.7 ^b	3566.5 ^a	2568.3 ^b	1541.4 ^c	2451.5 ^a	2666.0 ^b
GY	1393.8 ^a	1044.1 ^b	1650.2 ^a	1294.5 ^b	712.2 ^c	1023.7 ^a	1414.2 ^b

Means within a row followed by the same superscript letter are not significantly different at $p \leq 0.05$. NA = Not applicable. **Abbreviations:** CHAK= Chakwal, SD = Sowing date, DTF = Days to Flowering, DTP = Days to Pod formation, DTM = Days to Maturity, LAIX = Leaf Area Index at maximum, TSW = Thousand seed weight(g), GY = Grain Yield(kg/ha), TDM = total dry matter(kg/ha)

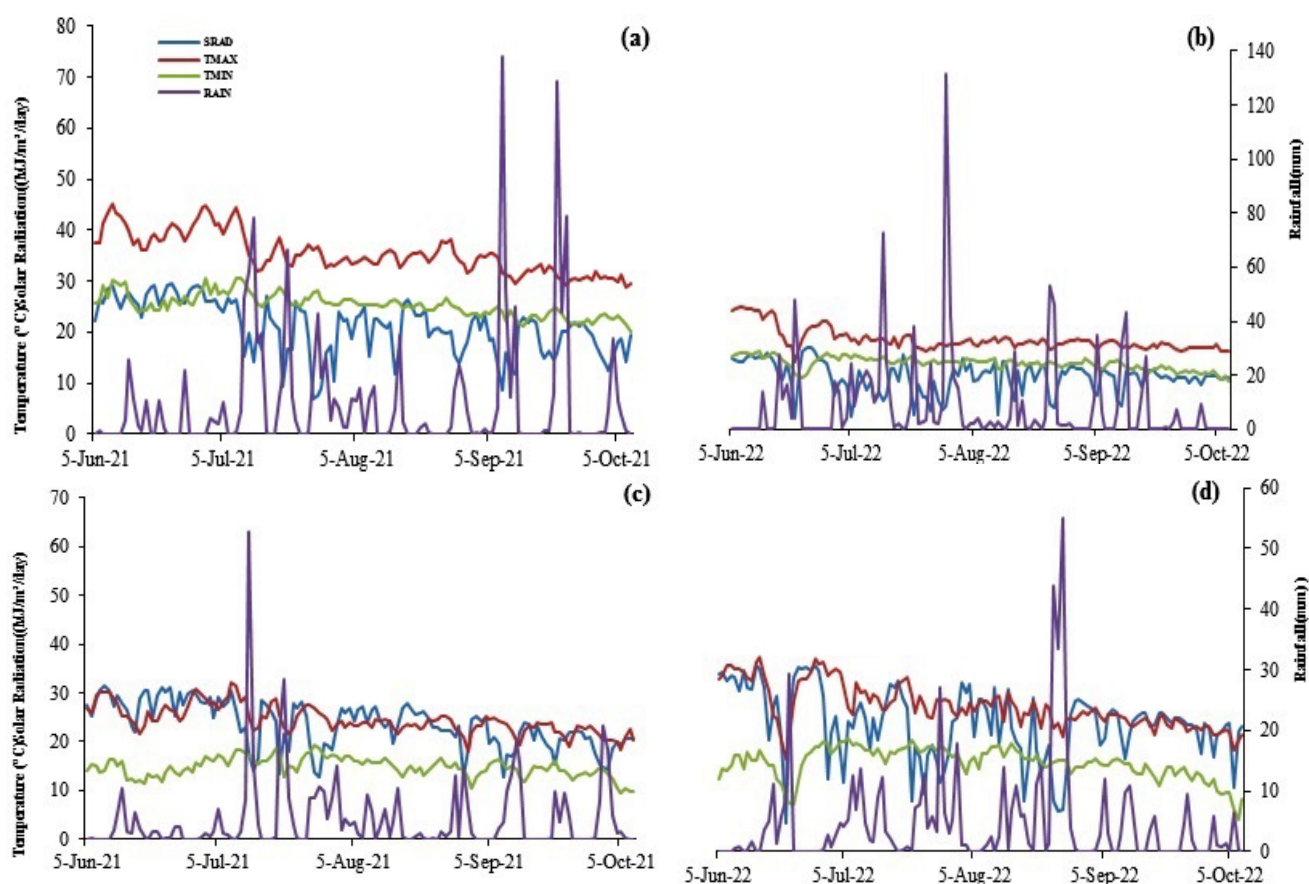


Figure 1: Daily weather conditions during the growing seasons at the experimental sites: (a) Chakwal 2021, (b) Chakwal 2022, (c) Swat 2021, and (d) Swat 2022.

Effect of sowing time and location on leaf area index at maximum (LAIX): The LAIX was significantly influenced by location, sowing date, and cultivar (ANOVA table S1). Soybean plants grown in Chakwal exhibited a markedly lower LAIX, (29% reduction) compared to those cultivated in Swat. Similarly, delayed sowing led to substantial declines in LAIX, where a 23% and 51% reduction was observed in plants sown on 25

June (SD2) and 15 July (SD3) compared with early sown plants on 5 June (SD1). Varietal comparison revealed that cultivar NARC-21 produced 15% higher LAIX than NARC-2 (Table 2). Interactions between sowing date and location imparted significant impacts on LAIX at maximum (ANOVA table S1). The highest leaf area was recorded at both locations under the earliest sowing date (SD1), followed by a gradual decline under SD2 and

SD3. Swat consistently exhibited greater leaf area values than Chakwal across all sowing dates (Figure 3a). The interaction between cultivar and location also revealed significant differences (ANOVA table S1). Cultivar, NARC-21 consistently outperformed NARC-2 regarding LAIX at both locations, with the difference being more pronounced in Swat (Figure 3 b). A significant interaction

between location and year was also evident (S1). Swat maintained higher LAIX values than Chakwal in both experimental years (Figure 3c). NARC-21 demonstrated higher leaf area compared to NARC-2 across all sowing dates, with peak values under SD1 followed by a declining trend under SD2 and SD3 (Figure 3d).

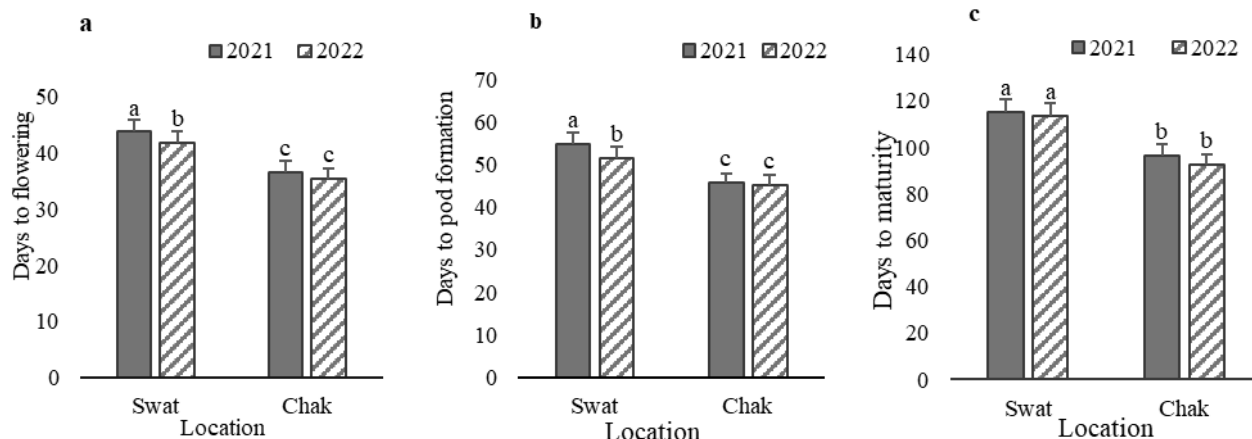


Figure 2: Interactive effect of year x location phenological attributes, (a) days to flowering, (b) days to pod formation, (c) days to maturity

The interactions between location, sowing date, and cultivar significantly affected maximum leaf area (ANOVA table S1). At both locations, the highest leaf area was observed in early sown plants (SD1) of NARC-21. Successive delays in sowing (SD2 and SD3), a

consistent reduction in leaf area was observed for both cultivars at both locations. The lowest leaf area measurements were recorded under SD3, for NARC-2 in Chakwal (Table 3).

Table 3: Interactive effects of location, sowing date, and cultivar, and location, cultivar, and year on grain yield (GY), leaf area index at maximum (LAIX), and grain yield across years (GY2) of soybean.

Sowing date	Cultivar	LAIX		GY1(kg/ha)		GY2(kg/ha)		
		Chakwal	Swat	Chakwal	Swat	year	Chakwal	Swat
SD1 (5June)	NARC-2	3.0425c	3.355b	1158d	1741.5b	2021	1022.3c	1178b
	NARC-21	3.2bc	4.295a	1502.7c	2198.5a	2021	1249b	1671.7a
SD2 (25June)	NARC-2	2de	2.29d	934e	1215.5d	2022	737d	1157.5b
	NARC-21	3.03c	3.4175b	1254.7d	1773.7b	2022	1168.2b	1568.2a
SD3 (15July)	NARC-2	1.1075g	1.9525e	547f	546.2f			
	NARC-21	1.4675f	2.2975d	868.2e	887.5e			

Note: Means within a column followed by the same superscript letter are not significantly different at $p \leq 0.05$.

Abbreviations: SD1 = Sowing date; LAIX = Leaf area index at maximum; GY1 = Grain yield from sowing date x cultivar x location interaction; GY2 = Grain yield from cultivar x year x location interaction.

Effect of sowing date, cultivar and location on yield attributes: Grain yield was significantly affected by location, sowing date, and cultivar (ANOVA table S1). The highest grain yield (GY) was obtained at Swat, which was 34% greater than that noted in Chakwal. Early sown (SD1) soybean plants yield 22% greater than late sowing (SD2), while SD3 showed a 45% reduction compared to SD1. Among cultivars, NARC-21 outyielded

NARC-2 by 38%. Data revealed that the thousand-seed weight (TSW) of soybean plants cultivated in Swat was 17% greater than that from Chakwal (Table 2; ANOVA table S1). Among sowing dates, SD1 produced the highest TSW, followed by SD2 and SD3, which respectively yielded 8 and 15% lower than early sown (SD1) seeds (Table 2). As expected, total dry matter (TDM) accumulation significantly varied across locations

and sowing dates (ANOVA table S1). Plants grown under irrigated conditions (Swat) produced 51% greater TDM than those at Chakwal. Among cultivars, NARC-21 accumulated 9% more TDM than NARC-2. Interactions between location and sowing dates remarkably influenced the grain yield as is evident from the data in ANOVA table S1. Swat consistently outperformed Chakwal, with early sowing (SD1) producing the highest yield at both locations (Figure 4a). Yields progressively declined as the sowing was delayed, and surprisingly, seed yield was statistically similar during the last plant date (SD3) at

both locations. Varietal comparison revealed that NARC-21 yielded significantly higher than NARC-2 at both locations; however, the overall yields were substantially lower at Chakwal than at Swat (Figure 4b). Experimental plants under irrigated conditions (Swat) maintained stable yields across both years, whereas under rainfed conditions (Chakwal), soybean yield declined in 2022 compared to 2021 (Figure 4c). Both cultivars exhibited the highest yield under SD1, with progressively lower yields under SD2 and SD3 (Figure 4d).

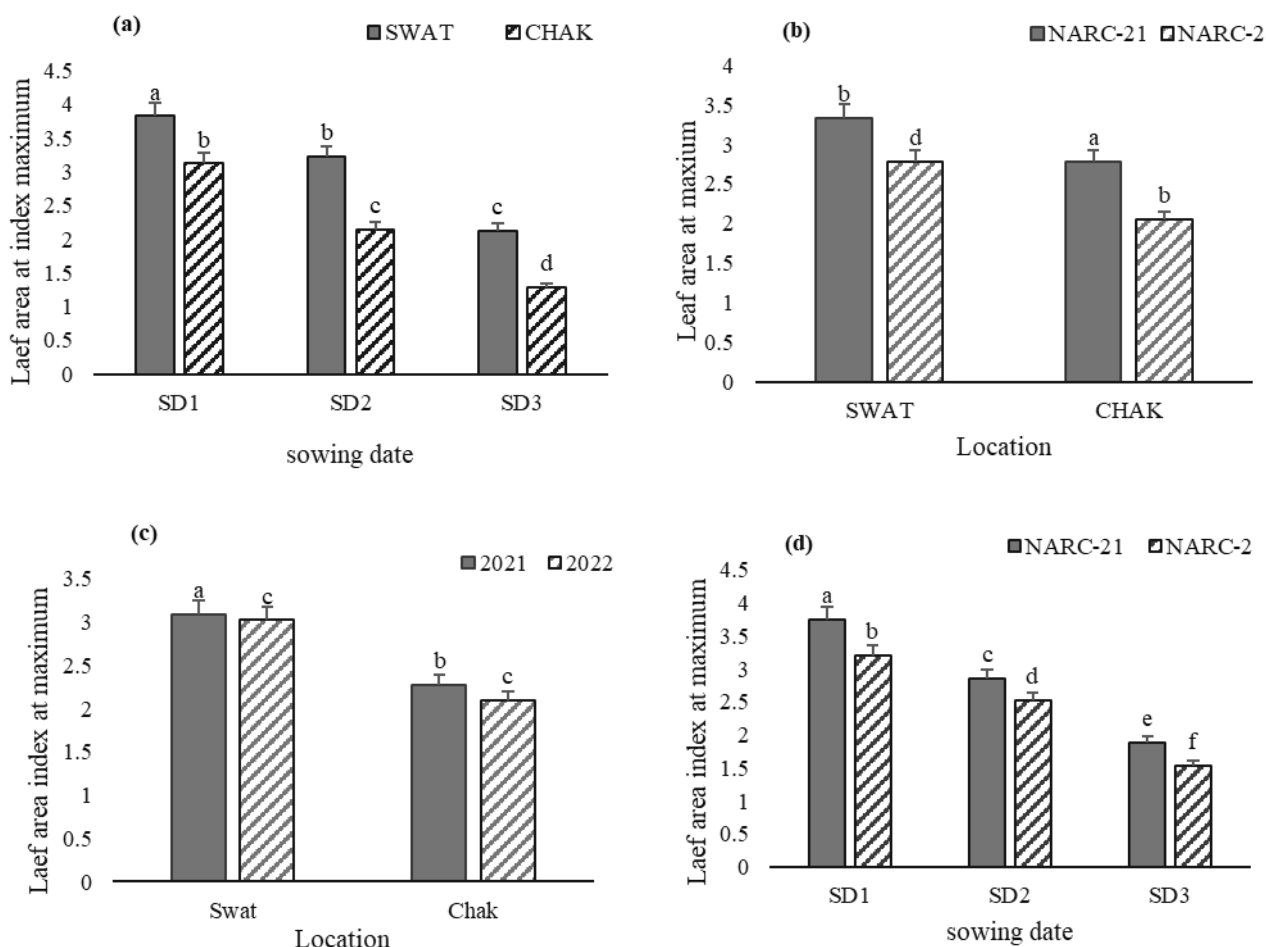


Figure 3: Interactive effects of sowing date, location, cultivar, and year on soybean leaf area index at maximum. (a) sowing date × location interaction; (b) cultivar × location interaction; (c) year × location interaction; (d) sowing date × cultivar interaction.

Soybean grain yield was significantly influenced by the location × sowing date × cultivar interaction (Table 3). Earlier sowing (SD1; June 5) resulted in higher yields than delayed sowings under both rainfed (Chakwal) and irrigated conditions (Swat). NARC-21 outperformed NARC-2 across all treatments, with the highest yield under SD1 at Swat and the lowest under

SD3 (July 15) for NARC-2 at both locations. A similar trend occurred in Chakwal, though yields were consistently lower than in Swat (Table 3). Further analysis of the cultivar × year × location interaction revealed that grain yields were significantly higher in 2021 compared to 2022 for both cultivars.

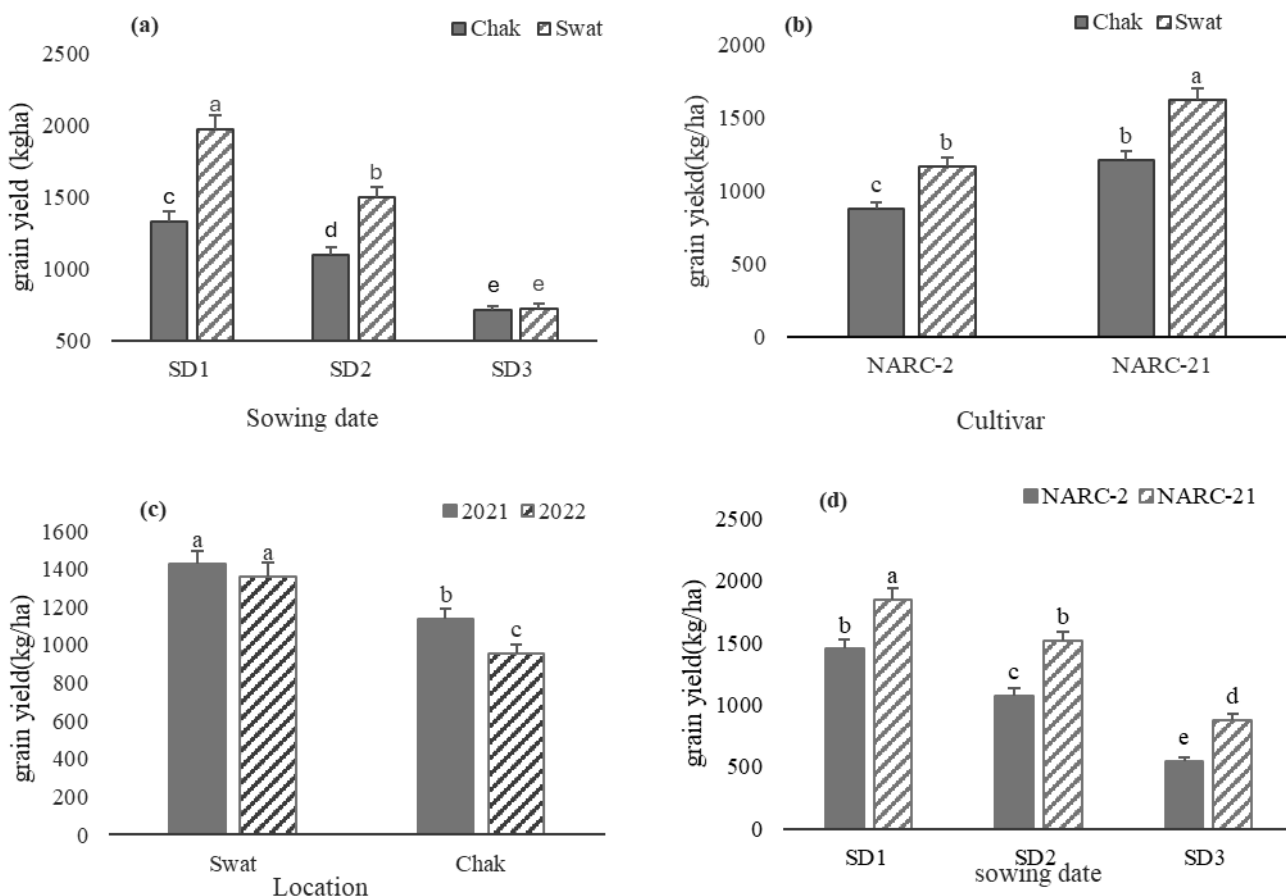


Figure 4: Interactive effects of sowing date, location, cultivar, and year on grain yield of soybean (a) sowing date × location interaction; (b) cultivar × location interaction; (c) year × location interaction; (d) sowing date × cultivar interaction.

Location	Dependent Variable	Independent variable	Linear Regression Equation	R ²	P-value
Chakwal	DTM	aveTmax	y = 0.0900Tmax + 25.38	0.45	>0.05
	DTM	aveTmin	y = 0.0731Tmin + 17.60	0.53	>0.05
	DTM	Total rainfall	y = 11.491Rainfall - 317.42	0.45	>0.05
	DTM	Total SRAD	y = 0.0270SRAD + 44.60	0.60	≤0.05
	GY	aveTmax	y = 165.59Tmax - 4553.10	0.73	≤0.05
	GY	aveTmin	y = 275.68Tmin - 5712.00	0.94	≤0.05
	GY	Total rainfall	y = 0.0296Rainfall + 63.52	0.70	≤0.05
	GY	Total SRAD	y = 0.9321SRAD - 677.94	0.91	≤0.05
	GY	DTM	y = 23.735DTM - 1197.90	0.70	≤0.05
	DTM	aveTmax	y = 5.6867Tmax - 16.94	0.89	≤0.05
Swat	DTM	aveTmin	y = 7.6297Tmin + 7.08	0.89	≤0.05
	DTM	Total rainfall	y = 0.1205Rainfall + 53.73	0.80	≤0.05
	DTM	Total SRAD	y = 35.652SRAD - 1638.50	0.73	≤0.05
	GY	aveTmax	y = 470.44Tmax - 9455.60	0.90	≤0.05
	GY	aveTmin	y = 630.75Tmin - 7462.00	0.95	≤0.05
	GY	Total rainfall	y = 0.0825Rainfall + 387.05	0.78	≤0.05
	GY	Total SRAD	y = 0.4671SRAD + 1782.20	0.80	≤0.05
	GY	DTM	y = 76.024DTM - 7288.80	0.90	≤0.05

Effects of environmental attributes on phenology and yield of soybean: Our study demonstrates how environmental traits influenced experimental plants grown in different agroecological zones (Table 4). The effect of T_{min} and T_{max} on DTM was strongly positive in Swat compared to Chakwal, with R^2 values ranging from 0.4 to 0.89. The influence of total SRAD on DTM was positive for both locations ($R^2 = 0.6 - 0.8$, $P \leq 0.05$), showing the delay in maturity with an increase in total SRAD. Similarly, the positive effect of rainfall was observed on DTM for Chakwal and Swat, ($R^2 = 0.45$ to 0.8 ; $p = \leq 0.05$ to >0.05). Similarly, the influence of environmental attributes on grain yield showed a notable difference at both locations. T_{max} and T_{min} temperatures showed a positive to strongly positive influence on soybean yield, with R^2 values ranging from 0.7 to 0.9 ($p \leq 0.05$). Similarly, total solar radiation (SRAD) and rainfall also exhibited a positive impact on yield ($R^2 = 0.7-0.9$, $p \leq 0.05$), indicating an overall increase in soybean production under these conditions.

DISCUSSION

The present study provides comprehensive insights into the effects of planting time and cultivar selection on soybean productivity across two contrasting agro-ecological zones in Pakistan. The results indicate that planting date, location, and cultivar factors significantly influence key agronomic traits, including phenological, growth, and yield. Sowing date significantly influenced phenological development, with early sowing extending the growth period and delayed sowing accelerating flowering and maturity (Ahmed *et al.*, 2015). Our results (Table 2) corroborate with this trend, demonstrating that later sowings shortened the crop cycle. The changes in phenological attributes with planting date may be attributed to the photoperiod sensitivity of soybean, as phenological transitions are hastened in response to reduced day lengths and lower temperatures (Lee *et al.*, 2019; Hou *et al.*, 2023). The growth attributes, such as LAIX, are significantly affected by sowing time, location, and year in soybean. Early sowing consistently resulted in elevated LAIX across both locations and cultivars (Figure 3a, d), likely due to an extended vegetative phase that delayed phenological progression and promoted enhanced leaf development (Clovis *et al.*, 2015). Location-specific differences in LAIX were also evident, with higher values observed in Swat compared to Chakwal (Figure 3b). This difference may be attributed to the stable water availability under irrigated conditions, which mitigated drought stress and promoted consistent vegetative growth (Scandurra *et al.*, 2024). Conversely, Chakwal's rainfed environment resulted in comparatively lower LAIX, consistent with earlier reports indicating yield reductions

of up to 50% under water-limited systems (Jaramillo *et al.*, 2020). Sowing time, location, and year had a significant influence on soybean yield attributes. Early sowing (SD1: 5 June) consistently produced higher grain yield and total biomass across both locations and years (Table 2), corroborating previous studies that emphasize the yield advantages of early sowing (Bashir *et al.*, 2010; Liu *et al.*, 2021). The yield improvement under early sowing was largely attributable to an extended vegetative phase, which facilitated higher leaf area index, enhanced canopy development, and prolonged dry matter accumulation (Sudhansu *et al.*, 2021). In contrast, delayed sowing accelerated phenological progression due to shortened photoperiod and reduced thermal time, curtailing the crop duration and limiting biomass accumulation and yield (Ahmed *et al.*, 2015; Hou *et al.*, 2023). Location-specific differences were also evident, with Swat (irrigated) exhibiting significantly higher yields compared to Chakwal (rainfed) (Figure 4a), a result attributable to consistent water availability that buffered against drought stress and supported optimal physiological functioning (Jaramillo *et al.*, 2020; Scandurra *et al.*, 2024). Conversely, the rainfed conditions at Chakwal, characterized by erratic precipitation patterns, led to reduced and more variable yields. Our results agree with Sincik *et al.* (2008), who reported a 45% yield decline in soybean grown under rainfed conditions compared to irrigated treatments, highlighting the critical role of water availability in maintaining yield potential. Kumari *et al.* (2019) demonstrated analogous climate-driven yield instability in Madhya Pradesh, where rainfed districts (Bhopal) consistently underperformed relative to regions with reliable moisture. Interannual variability further modulated yield outcomes; yields in 2021 were notably higher than in 2022 across both sites (Figure 4c), a pattern consistent with higher cumulative rainfall and solar radiation (SRAD) observed in 2021 (Figure 1), which improved soil moisture availability and extended the growing period (Rockström *et al.*, 2010; Martin *et al.*, 2022). Solar radiation and temperature played a critical role in regulating crop development and yield. Delayed sowing exposed the crop to declining SRAD and suboptimal temperatures, which constrained photosynthetic activity and reduced dry matter partitioning to reproductive organs (Villegas *et al.*, 2016; Moore *et al.*, 2021). Regression analysis (Table 4) revealed a strong positive association between grain yield and total SRAD during the maturity phase, underscoring the importance of radiation-driven photosynthesis in biomass accumulation and grain filling (Huang *et al.*, 2016; Yang *et al.*, 2022; Vercellino *et al.*, 2025). The decline in SRAD during late-season sowing reduced radiation-use efficiency, ultimately suppressing yield. Collectively, these findings highlight the critical role of optimized sowing dates, adequate solar radiation, and

moisture availability in maximizing soybean yield. In water-limited environments such as Chakwal, early sowing combined with moisture conservation strategies (i.e., aligning sowing with rainfall patterns) can enhance water use efficiency and yield stability (Ndomba *et al.*, 2010; Jelde *et al.*, 2024). These results underscore the need for site-specific agronomic management to improve productivity under variable climatic conditions. Delayed sowing significantly alters the thermal and radiative environment, reducing maximum and minimum temperatures and solar radiation (SRAD), which constrains thermal accumulation and accelerates crop development, thereby shortening the growth duration (Huang, 2015; Villegas *et al.*, 2016). Late sowing reduces thermal time and SRAD during critical stages, particularly from sowing to anthesis, limiting biomass production and yield potential (Table 4). SRAD emerged as a key determinant of grain yield, with early sowing enhancing total SRAD, photosynthetic activity, and biomass accumulation, resulting in higher yields. In contrast, delayed sowing reduced SRAD during reproductive stages, diminishing photosynthetic efficiency and grain filling. This pattern was consistent across cultivars, locations, and years, confirming the central role of SRAD in soybean productivity (Huang *et al.*, 2016; Yang *et al.*, 2019, 2022; Vercellino *et al.*, 2025). Our findings also highlight the importance of solar radiation (SRAD) and temperature, with cooler temperatures and higher SRAD in 2021 promoting extended crop duration and higher yields (Figure 1; Prasad *et al.*, 2018). Farmers can optimize yields by aligning sowing dates with favorable climatic conditions. Overall, strategies such as early sowing, resilient cultivars, and irrigation prioritization supported by policy and extension services can enhance soybean productivity under climatic uncertainty.

Conclusion: Early sowing under irrigated conditions significantly enhanced biomass and grain yield of soybean, whereas delayed sowing reduced growth duration and productivity due to limited exposure to solar radiation. Between cultivars, NARC-21 consistently outperformed NARC-2, demonstrating its better adaptation to local conditions. To optimize soybean production, farmers should prioritize early sowing and adopt high-yielding cultivars, such as NARC-21. Meanwhile, policymakers and extension services must promote region-specific planting guidelines and improved access to seeds. Future research should expand evaluations to include short-duration, drought-tolerant, and photoperiod-insensitive varieties, alongside long-term climate data, to strengthen resilience and productivity under changing agro-climatic conditions.

Data Availability: The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Conflict of Interest: The authors declare no conflict of interest.

Author's contributions: Farina Shaheen (experimental work and data analysis); Imran Mehmood (statistical analysis); Muhammad Farooq (review and editing); Saeed A. Asad (Research supervisor/principal investigator, reviewed the 1st draft and research coordination).

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Supplementary data

ANOVA table S1: Analysis of variance for different sowing dates on phenology, growth and yield attributes of soybean cultivars 2021-22

Source of variance	DF	DTF	DPT	DTM	LAIXM	TSW	GY (kg/ha)	TDM
Location (L)	1	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Sowing date (SD)	2	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Cultivar (C)	1	0.00**	0.00**	0.00**	0.1	0.38 ^{ns}	0.00**	0.00**
Year (Y)	1	0.43 ^{ns}	0.03*	0.44 ^{ns}	0.00**	0.35 ^{ns}	0.00**	0.00**
L*SD	2	0.08 ^{ns}	0.98 ^{ns}	0.09 ^{ns}	0.00**	0.72 ^{ns}	0.00**	0.00**
L*C	1	1.00 ^{ns}	0.31 ^{ns}	0.90 ^{ns}	0.00**	0.83 ^{ns}	0.00**	0.34 ^{ns}
L*Y	1	0.00*	0.00*	0.04*	0.00**	0.74 ^{ns}	0.00**	0.09 ^{ns}
Y *SD	2	0.56 ^{ns}	0.27 ^{ns}	0.87 ^{ns}	0.03*	0.96 ^{ns}	0.11 ^{ns}	0.44 ^{ns}
SD*C	2	0.78 ^{ns}	0.85 ^{ns}	0.73 ^{ns}	0.04*	0.72 ^{ns}	0.04*	0.26 ^{ns}
L*SD*C	2	0.56 ^{ns}	0.29 ^{ns}	0.70 ^{ns}	0.00	0.96 ^{ns}	0.04*	0.15 ^{ns}
L*C*Y	1	0.87 ^{ns}	0.17 ^{ns}	0.95 ^{ns}	0.00**	0.86 ^{ns}	0.00**	0.97 ^{ns}
R2		0.83	0.79	0.78	0.86	0.45	0.97	0.986
RMSE		1.05	1.34	2.26	0.45	16.1	86.2513	179.91

Abbreviation: Degrees of Freedom, DTF: Days to Flowering, DPT: Days to Pod Formation, DTM: Days to Maturity, TDM: Total Dry Matter, GY: Grain yield, TSW: 1000 seed weight, LAIXM: Leaf area at maximum, ns: Not significant, *: Significant at $p \leq 0.05$, **: Significant at $p \leq 0.01$