

Variation in Soybean Plant Height in Relation to Sowing Time and Plant Density

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Abstract. Soybean is a crop of great importance for the economic, ecological and agronomic advantages it provides. In the context of climate change, soybean crop presents certain performance risks in non-irrigated systems, as a result of water and thermal stress. The present study evaluated the development of soybean plants based on the plant height parameter (PH, cm) in relation to sowing date and plant density. The study and field experiments were carried out within ARDS Lovrin. The soybean crop was sown in three different periods: E I (17.04.2025), E II (28.04.2025), E III (12.05.2025). Within each sowing time, five density variants were tested: 45, 55, and 65 plants m⁻² with 25-cm row spacing (V1–V3), and 45 plants m⁻² with 60-cm and 80-cm row spacing (V4–V5). 15 experimental variants resulted, in three replications. Mann-Kendall Test indicated an increasing trend in the mean values of the PH parameter, $p < 0.001$. ANOVA test ($p < 0.001$) and Kruskal-Wallis test ($p = 0.0019$) indicated significant differences between the mean and median values. Dunn's Post Hoc test generated 105 comparative analyses between the experimental variants and resulted in 69 statistically significant differences, including five cases at the $p < 0.05$ level (*), eight cases at the $p < 0.01$ level (**), and 56 cases at the $p < 0.001$ level (***). In the multivariate analysis, the principal components (PC1, PC2) explained 96.211% of the total variance and identified the correlation of the variants with the sowing times in relation to the plant height parameter. The cluster analysis grouped the variants based on similarity in relation to the values of the PH parameter (cm), under conditions of Coph.corr. = 0.879. The recorded results present scientific and practical importance, with utility for agricultural practice in optimizing technology in soybean cultivation.

Keywords: clustering, comparative analysis, plant canopy, Post hoc test, soybean

INTRODUCTION

Soybean is an important crop worldwide, serving as a major source of both food and feed through its high protein and oil content (Pagano and Miransari, 2016; Hamza et al., 2024; Rotundo et al., 2024). Globally, most soybean production is obtained in the United States, Brazil, and Argentina, which together account for approximately 75% of the world's annual supply. Soybeans also represent the most widely traded agricultural commodity (Hamed et al., 2025). Within the European Union, Italy, France, and Romania have been the leading soybean-producing countries over the past decade (Popescu et al., 2024).

Climate change has increasingly affected soybean cultivation, primarily through water stress, reduced productivity, and declines in both yield and product quality—all of which impact farm sustainability (Thomasz et al., 2024; Zhao et al., 2025). Significant spatiotemporal variability has also been observed in soybean cropping patterns in response to changing climatic conditions (Peng et al., 2025).

Breeding programs and modern genetic techniques aim to improve soybean genotypes with respect to vegetative growth, stress tolerance, agronomic performance, yield, and grain quality (Vargas-Almendara et al., 2024; Monfort et al., 2025). Agronomic practices have been reviewed and adapted to align with these new genotypes, as well as with specific soil and climatic conditions, in order to achieve high-performing soybean crops (e Silva et al., 2023; Zhong and Zhong, 2024; Gai et al., 2025).

Soybean development has been studied in relation to sowing date, focusing on plant growth, crop development stages, and yield performance under diverse soil and climate conditions (Madias et al., 2021; Fordoński et al., 2023; Seo et al., 2024).

Light interception, photosynthetic rate, and dry matter accumulation in soybean have been analyzed with respect to crop uniformity and plant density (Xu et al., 2021). The phenomenon of plant lodging has also been examined in relation to plant density within specific crop rotation systems (Wang et al., 2023), while density tolerance has been assessed using phenotyping and dynamic modeling techniques (Sun et al., 2025).

Strong effects of sowing date and plant density on canopy structure, photosynthetic rate, and seed yield have been reported (Xu et al., 2024). Moreover, variable yield responses have been observed under different combinations of row spacing and plant density across varying temperature and humidity regimes (Carciochi et al., 2019; Prusiński and Nowicki, 2020).

The objective of this study was to evaluate the variation in soybean plant height in relation to sowing time and plant density, row spacing and seed density/m² at sowing, under non-irrigated crop conditions.

MATERIAL AND METHODS

The study was carried out at the Agricultural Research and Development Station (ARDS) Lovrin during the 2024–2025 agricultural year on soybean (*Glycine max* L.) crop. The research was conducted within the framework of the ADER 1.4.1 Project.

The experimental site is characterized by chernozem soil of medium fertility. Prior to sowing, the land was prepared through plowing, disc harrowing, and combinator operations to ensure a suitable seedbed for uniform germination. “IRIS TD”, an early soybean variety developed at Agricultural Research and Development Station (ARDS) Turda, was used as the biological material in this study.

Soybean was sown at three different dates:

- E I – April 17, 2025;
- E II – April 28, 2025;
- E III – May 12, 2025.

Within each sowing date, five plant density variants were established:

- V1 – 45 plants/m², 25 cm row spacing;
- V2 – 55 plants/m², 25 cm row spacing;
- V3 – 65 plants/m², 25 cm row spacing;
- V4 – 45 plants/m², 60 cm row spacing;
- V5 – 45 plants/m², 80 cm row spacing.

This design resulted in a total of 15 experimental variants, each replicated three times.

The crop was managed according to the standard soybean cultivation technology recommended for the region. The experiment was conducted under non-irrigated (rainfed) conditions. Climatic data for the experimental period were recorded by the ARDS Lovrin Meteorological Station and are presented in Table 1.

Table 1. Climatic conditions at the study location

Month/Decade 2025	Average air temperature (°C)	Sum of temperature (°C)	Average relative air humidity (%)	Precipitation (mm)
April/I	7.4	76.9	67	1.8
April/II	14.7	138.6	64	12.2
April/III	17.1	202.1	66	8.8
Monthly average/amount	13.8	-	66	22.8
May/I	16.3	163.0	66	25.2
May/II	12.9	129.2	66	20.0
May/III	16.3	179.2	75	22.0
Monthly average/amount	15.2	-	69	67.2
June/I	23.4	234.5	48	15.2
June/II	22.5	226	61	8.2
June/III	25.0	295.8	56	30
Monthly average/amount	25	-	55	53.4
July/I	23.9	238.64	48	15.2
July/II	22.5	223.6	61	8.2
July/III	25.2	350.3	56	30
Monthly average/amount	23.9	-	55	53.4
August/I	23.9	230.6	44	0.0
August/II	25.6	256.3	42	3.0
August/III	21.4	284.7	51	18.6
Monthly average/amount	23.6	-	48	29.4
September/I	24	179.9	44	4.6
September/II	19.9	139.2	68	20.4

Plant height (PH, cm) was evaluated under the experimental conditions. At physiological maturity, plant

samples (10 plants) were randomly collected from each variant and replication. In the laboratory, plant height was measured on the workbench using a tape measure with an accuracy of ± 0.5 mm.

The experimental data were recorded by variant and replication, then processed mathematically and statistically in accordance with the study objectives. Data analysis and graph generation were performed using Microsoft Excel, PAST software (Hammer et al., 2001), JASP software (2022), and Mathematica software (2024).

RESULTS AND DISCUSSION

Soybean plant height, as influenced by sowing date and experimental variant, ranged from 43.90 ± 0.17 cm (E I V3) to 51.50 ± 0.36 cm (E III V5). Within each sowing date, plant height varied as follows: E I: 43.90 ± 0.17 cm to 46.00 ± 0.27 cm, E II: 45.50 ± 0.67 cm to 48.30 ± 0.67 cm, E III: 49.50 ± 0.35 cm to 51.50 ± 0.36 cm.

The graphical distribution of soybean plant height (PH, cm) across all experimental variants (from E I V1 to E III V5) is illustrated in Figure 1.

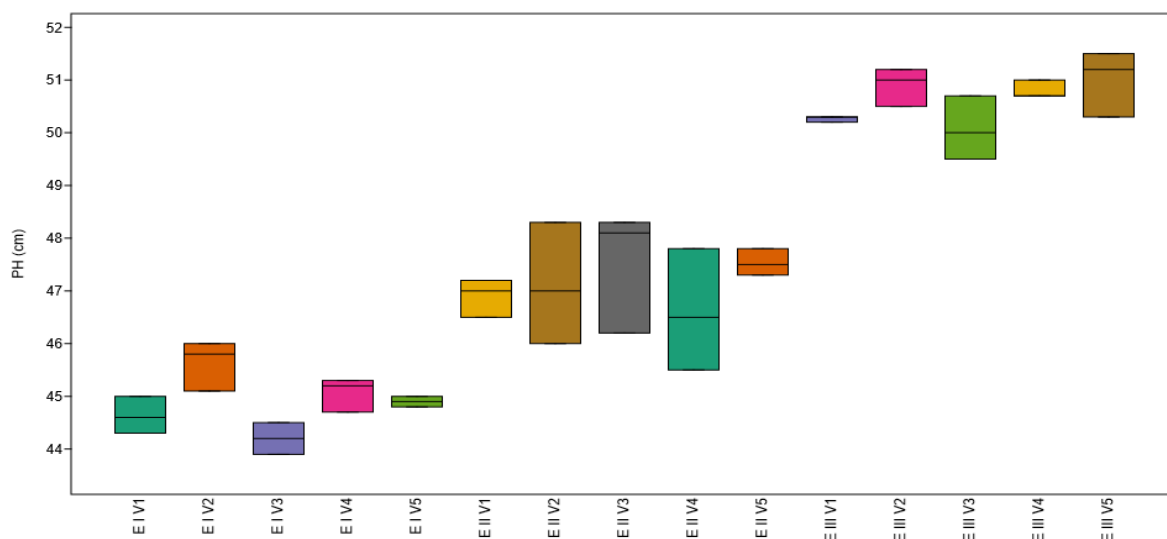


Figure 1. Soybean plants height, graphic representation

The Mann–Kendall test indicated a statistically significant increasing trend in the data series of average soybean plant height (PH, cm), under statistically reliable conditions ($S = 82$, $Z = 4.0134$, $p < 0.001$).

The linear regression model (Ordinary Least Squares Regression, OLSR) confirmed this trend, showing the distribution of PH values with statistically significant parameters presented in Table 2, and their graphical representation illustrated in Figure 2.

Table 2. Statistical parameters, OLSR, soybean plant height

Statistical Parameters	Statistical parameter values		
Slope a:	0.5184	Std. error a:	0.0533
t:	9.7324	p (slope):	2.46E-07
Intercept b:	43.3950	Std. error b:	0.4843
95% bootstrapped confidence intervals (N=1999):			
Slope a:	(0.40824, 0.60779)		
Intercept b:	(42.602, 44.503)		
Correlation:			
r:	0.9377		
r ² :	0.8793		
t:	9.7324		
p (uncorr.):	2.46E-07		
Permutation p:	0.0001		

The ANOVA test applied to the OLSR model also demonstrated statistical significance ($p < 0.001$). The analysis of residuals indicated a normal distribution, confirming the adequacy and validity of the regression model.

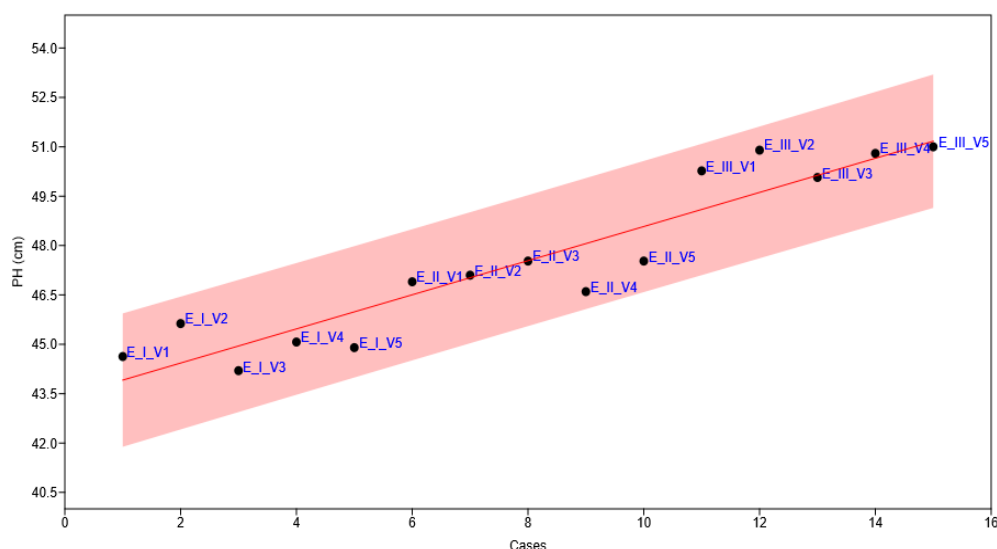


Figure 2. Linear fit plot, plant height in soybean on experimental trials

The variation of the PH parameter was analyzed depending on the density of soybean plants (plt/m^2) and the distance between plant rows (cm) by quadratic regression.

The result was Equation (1), which described the variation of the PH parameter in relation to Pd (x – axis) and the distance between rows Rs (y – axis), under conditions of $R^2 = 0.997$, $F = 802.463$, $p < 0.001$. The graphical distribution of PH values in relation to Pd and Rs is presented in Figure 3.

$$\text{PH} = a x^2 + b y^2 + c x + d y + e xy + f \quad (1)$$

where: PH – plant height (cm);

x – Pd – plant density (plt/m^2);

y – Rs – row spacing (cm);

a, b, c, d, e, f – coefficients of the equation (1);

$a = -0.00611111$; $b = 0.00017748$; $c = 1.32775933$; $d = 1.17122943$; $e = -0.02622148$; $f = 0$

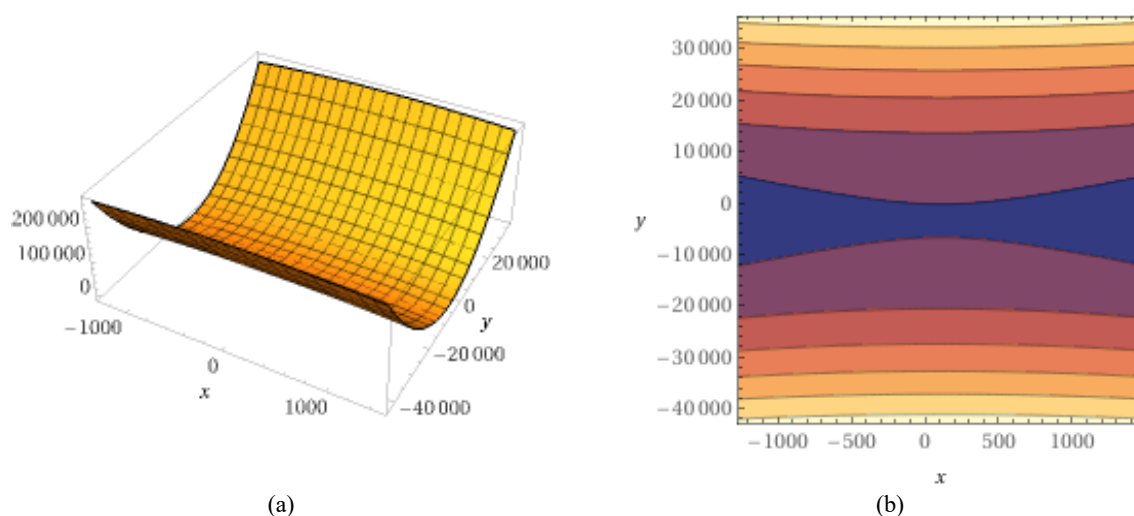


Figure 3. Graphical representation of the PH variation in soybeans, in relation to Pd (x – axis) and Ps (y – axis)

The ANOVA test (for equality of means) showed significant differences between the mean values for the soybean plant height parameter, in relation to the experimental variants, Table 3. The Kruskal-Wallis test (test for equal medians) also confirmed the existence of significant differences between the median values for the soybean plant height parameter, with $H(\chi^2) = 12.5$, H_c (tie corrected) = 12.52, $p = 0.0019$.

Table 3. ANOVA Test results

Statistical parameters	Sum of sqrs	df	Mean square	F	p (same)
Between groups:	83.1140	2	41.5570	202.900	5.62E-10
Within groups:	2.4579	12	0.2048		
Total:	85.5718	14	1.00E-05		
Components of variance (only for random effects):					
Var(group):	8.2704	Var(error):	0.2048	ICC:	0.9758
omega ² :	0.9642				
Levene's test for homogeneity of variance, from means	p (same):	0.9220			
Levene's test, from medians	p (same):	0.9247			
Welch F test in the case of unequal variances:		F=182.3, df=7.902, p=2.442E-07			
Bayes factor:		1.794E07 (decisive evidence for unequal means)			

Based on the differences between the mean and median values of the PH parameters in soybean plants, statistically confirmed, the Post hoc test was applied, with the results in Table 4.

Table 4. Post Hoc Test results

Experimental Trials		Mean Difference	95% CI for Mean Difference		Statistical safety parameters		
			Lower	Upper	t	p	Sig
E I V1	E I V2	-1.000	-2.849	0.849	-1.993	0.787	ns
	E I V3	0.433	-1.415	2.282	0.864	1.000	ns
	E I V4	-0.433	-2.282	1.415	-0.864	1.000	ns
	E I V5	-0.267	-2.115	1.582	-0.532	1.000	ns
	E II V1	-2.267	-4.115	-0.418	-4.518	0.006	**
	E II V2	-2.467	-4.315	-0.618	-4.917	0.002	**
	E II V3	-2.900	-4.749	-1.051	-5.780	< .001	***
	E II V4	-1.967	-3.815	-0.118	-3.920	0.029	*
	E II V5	-2.900	-4.749	-1.051	-5.780	< .001	***
	E III V1	-5.633	-7.482	-3.785	-11.228	< .001	***
	E III V2	-6.267	-8.115	-4.418	-12.491	< .001	***
	E III V3	-5.433	-7.282	-3.585	-10.830	< .001	***
	E III V4	-6.167	-8.015	-4.318	-12.292	< .001	***
	E III V5	-6.367	-8.215	-4.518	-12.690	< .001	***
E I V2	E I V3	1.433	-0.415	3.282	2.857	0.271	ns
	E I V4	0.567	-1.282	2.415	1.129	0.997	ns
	E I V5	0.733	-1.115	2.582	1.462	0.973	ns
	E II V1	-1.267	-3.115	0.582	-2.525	0.454	ns
	E II V2	-1.467	-3.315	0.382	-2.923	0.242	ns
	E II V3	-1.900	-3.749	-0.051	-3.787	0.039	*
	E II V4	-0.967	-2.815	0.882	-1.927	0.822	ns
	E II V5	-1.900	-3.749	-0.051	-3.787	0.039	*

	E III V1	-4.633	-6.482	-2.785	-9.235	< .001	***
	E III V2	-5.267	-7.115	-3.418	-10.498	< .001	***
	E III V3	-4.433	-6.282	-2.585	-8.837	< .001	***
	E III V4	-5.167	-7.015	-3.318	-10.298	< .001	***
	E III V5	-5.367	-7.215	-3.518	-10.697	< .001	***
E I V3	E I V4	-0.867	-2.715	0.982	-1.727	0.908	ns
	E I V5	-0.700	-2.549	1.149	-1.395	0.981	ns
	E II V1	-2.700	-4.549	-0.851	-5.382	< .001	***
	E II V2	-2.900	-4.749	-1.051	-5.780	< .001	***
	E II V3	-3.333	-5.182	-1.485	-6.644	< .001	***
	E II V4	-2.400	-4.249	-0.551	-4.784	0.003	**
	E II V5	-3.333	-5.182	-1.485	-6.644	< .001	***
	E III V1	-6.067	-7.915	-4.218	-12.092	< .001	***
	E III V2	-6.700	-8.549	-4.851	-13.355	< .001	***
	E III V3	-5.867	-7.715	-4.018	-11.694	< .001	***
	E III V4	-6.600	-8.449	-4.751	-13.155	< .001	***
	E III V5	-6.800	-8.649	-4.951	-13.554	< .001	***
E I V4	E I V5	0.167	-1.682	2.015	0.332	1.000	ns
	E II V1	-1.833	-3.682	0.015	-3.654	0.054	ns
	E II V2	-2.033	-3.882	-0.185	-4.053	0.021	*
	E II V3	-2.467	-4.315	-0.618	-4.917	0.002	**
	E II V4	-1.533	-3.382	0.315	-3.056	0.189	ns
	E II V5	-2.467	-4.315	-0.618	-4.917	0.002	**
	E III V1	-5.200	-7.049	-3.351	-10.365	< .001	***
	E III V2	-5.833	-7.682	-3.985	-11.627	< .001	***
	E III V3	-5.000	-6.849	-3.151	-9.966	< .001	***
	E III V4	-5.733	-7.582	-3.885	-11.428	< .001	***
E I V5	E III V5	-5.933	-7.782	-4.085	-11.826	< .001	***
	E II V1	-2.000	-3.849	-0.151	-3.986	0.024	*
	E II V2	-2.200	-4.049	-0.351	-4.385	0.009	**
	E II V3	-2.633	-4.482	-0.785	-5.249	< .001	***
	E II V4	-1.700	-3.549	0.149	-3.388	0.097	ns
	E II V5	-2.633	-4.482	-0.785	-5.249	< .001	***
	E III V1	-5.367	-7.215	-3.518	-10.697	< .001	***
	E III V2	-6.000	-7.849	-4.151	-11.959	< .001	***
	E III V3	-5.167	-7.015	-3.318	-10.298	< .001	***
	E III V4	-5.900	-7.749	-4.051	-11.760	< .001	***
E II V1	E III V5	-6.100	-7.949	-4.251	-12.159	< .001	***
	E II V2	-0.200	-2.049	1.649	-0.399	1.000	ns
	E II V3	-0.633	-2.482	1.215	-1.262	0.992	ns
	E II V4	0.300	-1.549	2.149	0.598	1.000	ns
	E II V5	-0.633	-2.482	1.215	-1.262	0.992	ns
	E III V1	-3.367	-5.215	-1.518	-6.711	< .001	***
	E III V2	-4.000	-5.849	-2.151	-7.973	< .001	***
	E III V3	-3.167	-5.015	-1.318	-6.312	< .001	***
	E III V4	-3.900	-5.749	-2.051	-7.774	< .001	***

	E III V5	-4.100	-5.949	-2.251	-8.172	< .001	***
	E II V3	-0.433	-2.282	1.415	-0.864	1.000	ns
	E II V4	0.500	-1.349	2.349	0.997	0.999	ns
	E II V5	-0.433	-2.282	1.415	-0.864	1.000	ns
E II V2	E III V1	-3.167	-5.015	-1.318	-6.312	< .001	***
	E III V2	-3.800	-5.649	-1.951	-7.574	< .001	***
	E III V3	-2.967	-4.815	-1.118	-5.913	< .001	***
	E III V4	-3.700	-5.549	-1.851	-7.375	< .001	***
	E III V5	-3.900	-5.749	-2.051	-7.774	< .001	***
	E II V4	0.933	-0.915	2.782	1.860	0.854	ns
	E II V5	6.148×10^{-15}	-1.849	1.849	1.225×10^{-14}	1.000	ns
E II V3	E III V1	-2.733	-4.582	-0.885	-5.448	< .001	***
	E III V2	-3.367	-5.215	-1.518	-6.711	< .001	***
	E III V3	-2.533	-4.382	-0.685	-5.049	0.002	**
	E III V4	-3.267	-5.115	-1.418	-6.511	< .001	***
	E III V5	-3.467	-5.315	-1.618	-6.910	< .001	***
	E II V5	-0.933	-2.782	0.915	-1.860	0.854	ns
E II V4	E III V1	-3.667	-5.515	-1.818	-7.308	< .001	***
	E III V2	-4.300	-6.149	-2.451	-8.571	< .001	***
	E III V3	-3.467	-5.315	-1.618	-6.910	< .001	***
	E III V4	-4.200	-6.049	-2.351	-8.372	< .001	***
	E III V5	-4.400	-6.249	-2.551	-8.770	< .001	***
	E III V1	-2.733	-4.582	-0.885	-5.448	< .001	***
E II V5	E III V2	-3.367	-5.215	-1.518	-6.711	< .001	***
	E III V3	-2.533	-4.382	-0.685	-5.049	0.002	**
	E III V4	-3.267	-5.115	-1.418	-6.511	< .001	***
	E III V5	-3.467	-5.315	-1.618	-6.910	< .001	***
	E III V2	-0.633	-2.482	1.215	-1.262	0.992	ns
E III V1	E III V3	0.200	-1.649	2.049	0.399	1.000	ns
	E III V4	-0.533	-2.382	1.315	-1.063	0.999	ns
	E III V5	-0.733	-2.582	1.115	-1.462	0.973	ns
	E III V3	0.833	-1.015	2.682	1.661	0.929	ns
E III V2	E III V4	0.100	-1.749	1.949	0.199	1.000	ns
	E III V5	-0.100	-1.949	1.749	-0.199	1.000	ns
	E III V4	-0.733	-2.582	1.115	-1.462	0.973	ns
E III V3	E III V5	-0.933	-2.782	0.915	-1.860	0.854	ns
E III V4	E III V5	-0.200	-2.049	1.649	-0.399	1.000	ns

Notes: * significance at the $p < 0.05$ level; ** significance at the $p < 0.01$ level; *** significance at the $p < 0.001$ level; ns – no statistical significance

The Post Hoc test was applied to compare the experimental data across the three sowing periods (E I, E II, E III) and the five density-spacing variants (V1–V5) within each sowing period, resulting in a total of 105 pairwise comparisons (SE = 0.502; SE – Standard Error).

Based on the results presented in Table 4, 69 statistically significant differences were identified: five at the $p < 0.05$ level (*), eight at the $p < 0.01$ level (**), and 56 at the $p < 0.001$ level (***).

In 36 comparisons, the differences were not statistically significant ($p > 0.05$; ns – not significant).

The multivariate analysis (PCA) revealed clear correlations between the experimental variants (V1–V5) and sowing periods (E I–E III) in relation to soybean plant height (PH). The distribution and grouping of these

relationships are illustrated in Figure 4.

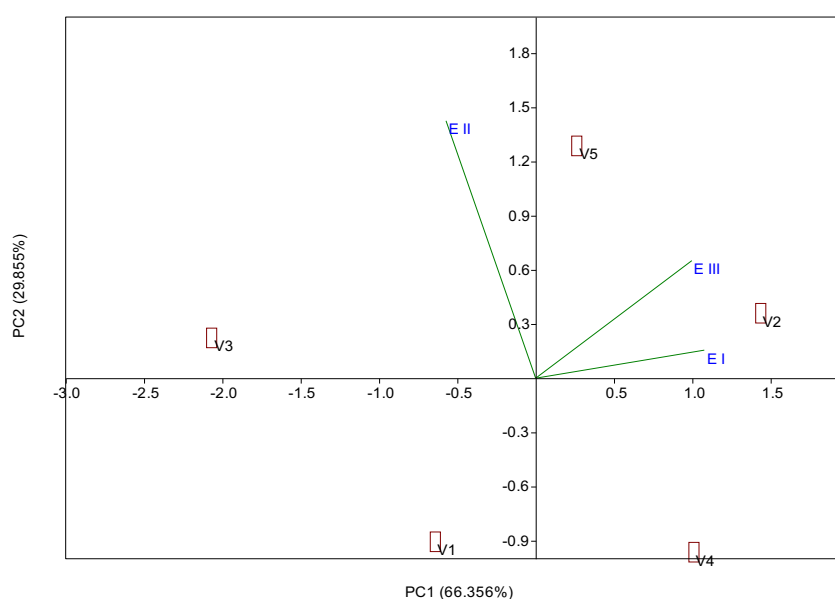


Figure 4. PCA diagram with the distribution of variants in relation to soybean sowing times

Component PC1 explained 66.356% of variance, and PC2 explained 29.855% of variance. Variant V5 was positioned intermediately between E III and E II, and variant V2 was positioned intermediately between E III and E I. Variants V1, V3 and V4 were positioned independently of the sowing times.

The score recorded by the variants in relation to the principal components is presented in Table 5, and the loading values of the sowing periods (as factors) in the principal components are presented in Table 6.

Table 5. Variant score in Principal Components

	PC 1	PC 2	PC 3
V1	-0.6406	-0.9058	0.0613
V2	1.4366	0.3599	0.5340
V3	-2.0685	0.2230	0.1351
V4	1.0103	-0.9634	-0.3434
V5	0.2623	1.2863	-0.3869

Table 6. Factor loadings in the Principal Components

	PC 1	PC 2	PC 3
E I	0.6836	0.0987	0.7232
E II	-0.3636	0.9052	0.2202
E III	0.6329	0.4135	-0.6546

The cluster analysis of the experimental trials (E I, E II, E III; V1–V5) grouped the variants according to their similarity in plant height (PH, cm) values, with a cophenetic correlation coefficient (Coph.corr.) of 0.879, indicating a high degree of clustering reliability (Figure 5).

The analysis revealed the formation of three distinct clusters corresponding to the three sowing periods (E I, E II, E III), in which sowing time acted as the primary discriminating factor. Within each cluster, subclusters were formed based on the similarity among the density–spacing variants (V1–V5), considered as a secondary factor.

The highest level of similarity at the experiment level was observed within cluster E III, between variants E III V2 and E III V4, and between E III V2 and E III V5, both with a Similarity and Distance Index (SDI) = 0.41.

In cluster E II, a strong similarity was found between variants E II V1 and E II V5 (SDI = 1.12), while in cluster E I, the closest relationship was recorded between E I V1 and E I V3 (SDI = 0.75). The complete set of Similarity and Distance Index (SDI) values is presented in Table 7.

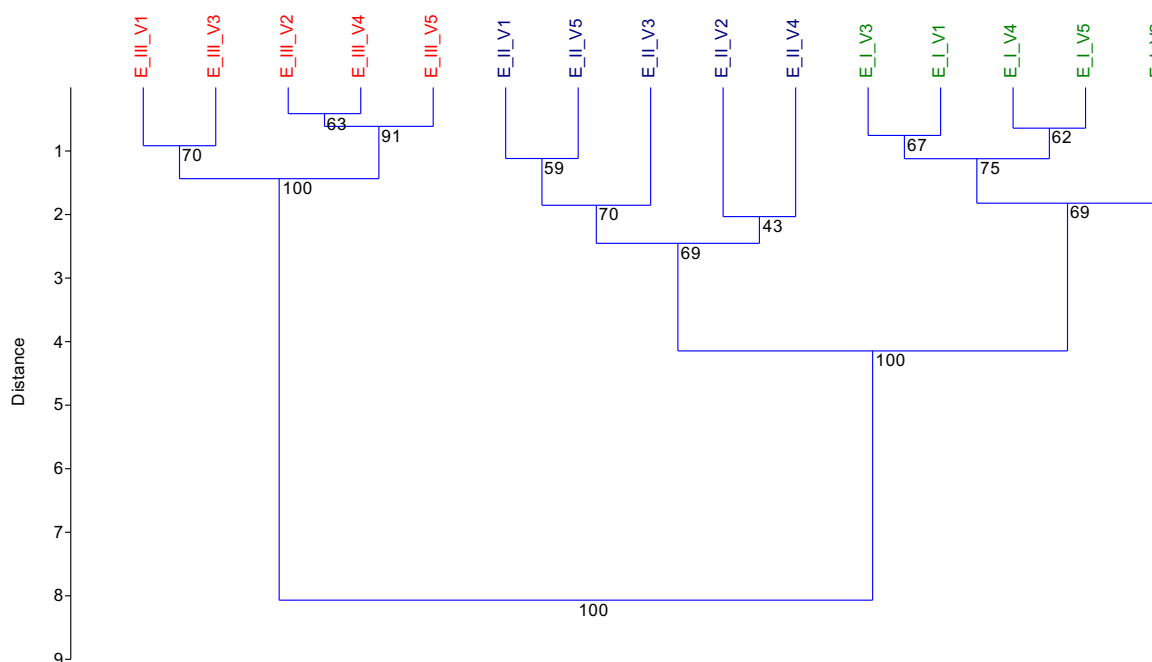


Figure 5. Cluster diagram

Table 7. SDI values for experimental variants in soybean, in relation to PH parameter

	E I V1	E I V2	E I V3	E I V4	E I V5	E II V1	E II V2	E II V3	E II V4	E II V5	E III V1	E III V2	E III V3	E III V4	E III V5
E I V1		1.87	0.75	0.83	0.79	4.00	4.42	5.45	3.73	5.08	9.77	10.90	9.49	10.71	11.11
E I V2	1.87		2.58	1.37	1.46	2.22	2.99	3.91	2.76	3.33	8.06	9.18	7.71	8.97	9.39
E I V3	0.75	2.58		1.53	1.34	4.74	5.17	6.12	4.42	5.82	10.52	11.64	10.23	11.45	11.85
E I V4	0.83	1.37	1.53		0.64	3.31	3.77	4.67	2.93	4.35	9.02	10.14	8.76	9.95	10.35
E I V5	0.79	1.46	1.34	0.64		3.50	4.20	4.81	3.40	4.57	9.30	10.40	8.98	10.22	10.59
E II V1	4.00	2.22	4.74	3.31	3.50		1.84	2.10	2.20	1.12	5.86	6.96	5.50	6.77	7.17
E II V2	4.42	2.99	5.17	3.77	4.20	1.84		3.30	2.03	1.99	5.74	6.92	5.59	6.67	7.20
E II V3	5.45	3.91	6.12	4.67	4.81	2.10	3.30		2.83	1.61	4.98	5.94	4.71	5.86	6.05
E II V4	3.73	2.76	4.42	2.93	3.40	2.20	2.03	2.83		2.56	6.56	7.66	6.49	7.50	7.87
E II V5	5.08	3.33	5.82	4.35	4.57	1.12	1.99	1.61	2.56		4.75	5.85	4.42	5.66	6.06
E III V1	9.77	8.06	10.52	9.02	9.30	5.86	5.74	4.98	6.56	4.75		1.18	0.92	0.95	1.50
E III V2	10.90	9.18	11.64	10.14	10.40	6.96	6.92	5.94	7.66	5.85	1.18		1.66	0.41	0.41
E III V3	9.49	7.71	10.23	8.76	8.98	5.50	5.59	4.71	6.49	4.42	0.92	1.66		1.42	1.90
E III V4	10.71	8.97	11.45	9.95	10.22	6.77	6.67	5.86	7.50	5.66	0.95	0.41	1.42		0.81
E III V5	11.11	9.39	11.85	10.35	10.59	7.17	7.20	6.05	7.87	6.06	1.50	0.41	1.90	0.81	

The canopy structure of soybean crops plays a key role in the photosynthetic process and in yield formation, being influenced not only by intrinsic plant factors (genetic background) but also by environmental and technological conditions and their interactions (He et al., 2024; Xu et al., 2024; Li et al., 2025).

Plant height in soybean is considered a key agronomic trait, directly affecting yield formation and overall crop performance (Ling et al., 2025). Previous studies have analyzed the genetic determination of this trait, highlighting the influence of both genetic and environmental interactions on height variability (Yang et al., 2021).

In the present study, the average soybean plant height varied significantly among sowing dates, ranging from 44.89 cm (E I) to 47.13 cm (E II) and 50.61 cm (E III). Within each sowing period, variation among the density–spacing variants was relatively small:

- E I: PH ranged from 44.20 cm (V3) to 45.63 cm (V2);
- E II: PH ranged from 46.60 cm (V4) to 47.53 cm (V3, V5);
- E III: PH ranged from 50.07 cm (V3) to 51.00 cm (V5).

Figure 2 shows that the smallest plant heights were observed in soybeans sown in mid-April, while the tallest plants occurred in late-sown soybeans in May.

It is well established that plant density influences height growth in many crops (Postma et al., 2021; Djaman et al., 2022; Miao et al., 2024). In soybean, plants exhibit plasticity in both height and branching, depending on density (Carciochi et al., 2019; Yoshihira et al., 2023; Xu et al., 2024). The observed increase in height under higher plant densities is commonly interpreted as a photomorphogenic response to competition for light (Xiao et al., 2006; Nagashima and Hikosaka, 2011). Several mathematical models have been developed to describe the relationships between crop growth and environmental factors such as light, water, and nutrients, with the aim of optimizing cultivation technologies (Boldea and Sala, 2010; Lu et al., 2024; Peng et al., 2025).

The Dunn's Post Hoc test revealed significant differences in 69 pairwise comparisons. The E III sowing period produced the highest PH values, followed by E II and E I, respectively. Variants from E III (V1–V5) consistently showed an advantage over the other experimental combinations.

The multivariate analysis (PCA) highlighted the interaction between sowing time and density–spacing variant ($E \times V$) as a key factor influencing plant height. The PCA diagram showed strong associations between $E \text{ III} \times V2$ and $E \text{ III} \times V5$ with higher PH values, while V1, V3, and V4 displayed independent positioning, indicating weaker correlations.

Finally, the cluster analysis identified the levels of similarity among experimental variants based on PH values, confirming the grouping patterns described by the PCA and reinforcing the influence of sowing time as the primary discriminating factor.

CONCLUSIONS

The interaction between sowing time (E I, E II, E III) and experimental variants (V1–V5) resulted in clear variation in soybean plant height under the study conditions. Sowing time had a significantly greater influence on plant height than the differences among plant density variants. The highest values for plant height were consistently recorded for the E III sowing period, across all variants, compared with E II and E I.

Under non-irrigated conditions, average plant height ranged from 44.89 cm (E I) to 50.61 cm (E III), with an intermediate mean of 47.13 cm for E II. Within each sowing period, plant density did not cause statistically significant differences in plant height.

According to the ANOVA and Kruskal–Wallis tests, statistically significant differences were observed between mean and median values. The Dunn's Post Hoc test generated 105 pairwise comparisons, of which 69 showed statistical significance: five at $p < 0.05$ (*), eight at $p < 0.01$ (**), and fifty-six at $p < 0.001$ (***).

The principal component analysis (PCA) revealed strong correlations between sowing time and plant density variants with respect to plant height, with the first two components explaining a substantial proportion of the total variance. Cluster analysis confirmed the similarity levels among density variants within each sowing period.

These results hold both scientific and practical relevance for optimizing soybean cultivation technologies under rainfed (non-irrigated) conditions, emphasizing plant height as an important agronomic trait linked to grain yield formation and overall crop performance.

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REFERENCES

1. Boldea M., Sala F. Optimizing economic indicators in the case of using two types of state-subsidized chemical fertilizers for agricultural production. AIP Conference Proceedings, 2010, 1281(1), 1390-1393. <https://doi.org/10.1063/1.3497988>
2. Carciochi W.D., Schwalbert R., Andrade F.H., Corassa G.M., Carter P., Gaspar A.P., Schmidt J., Ciampitti I.A. Soybean seed yield response to plant density by yield environment in North America. Agronomy Journal, 2019, 111(4), 1923-1932. <https://doi.org/10.2134/agronj2018.10.0635>

3. Djaman K., Allen S., Djaman D.S., Koudahe K., Irmak S., Puppala N., Darapuneni M.K., Angadi S.V. Planting date and plant density effects on maize growth, yield and water use efficiency. *Environmental Challenges*, 2022, 6, 100417. <https://doi.org/10.1016/j.envc.2021.100417>
4. e Silva J.A.G., Costa K.A.dP., da Silva L.M., Severiano E.dC., Silva F.G., Habermann E., Martinez C.A., Vilela L., da Silva A.G., Costa A.C., Costa J.V.C.P., de Oliveira K.J. Integrated systems improve the sustainability of soybean cultivation in the tropical region. *Frontiers in Sustainable Food Systems*, 2023, 7, 1224530. <https://doi.org/10.3389/fsufs.2023.1224530>
5. Fordoński G., Okorski A., Olszewski J., Dąbrowska J., Pszczółkowska A. The effect of sowing date on the growth and yield of soybeans cultivated in North-Eastern Poland. *Agriculture*, 2023, 13(12), 2199. <https://doi.org/10.3390/agriculture13122199>
6. Gai Y., Liu S., Zhang Z., Wei J., Wang H., Liu L., Bai Q., Qin Q., Zhao C., Zhang S., Xiang N., Zhang X. Integrative approaches to soybean resilience, productivity, and utility: A review of genomics, computational modeling, and economic viability. *Plants*, 2025, 14(5), 671. <https://doi.org/10.3390/plants14050671>
7. Hamed R., Lesk C., Shepherd T.G., Goulart H.M.D., van Garderen L., van den Hurk B., Coumou D. One-third of the global soybean production failure in 2012 is attributable to climate change. *Communications Earth & Environment*, 2025, 6, 199. <https://doi.org/10.1038/s43247-025-02171-x>
8. Hammer Ø., Harper D.A.T., Ryan P.D. PAST: Paleontological Statistics software package for education and data analysis. *Palaeontologia Electronica*, 2001, 4(1), 1-9.
9. Hamza M., Basit A.W., Shehzadi I., Tufail U., Hassan A., Hussain T., Siddique M.U., Hayat H.M. Global impact of soybean production: A review. *Asian Journal of Biochemistry, Genetics and Molecular Biology*, 2024, 16(2), 12-20. <https://doi.org/10.9734/ajbgmb/2024/v16i2357>
10. He S., Li X., Chen M., Xu X., Zhang W., Chi H., Shao P., Tang F., Gong T., Guo M., Xu M., Yang W., Liu W. Excellent canopy structure in soybeans can improve their photosynthetic performance and increase yield. *Agriculture*, 2024, 14(10), 1783. <https://doi.org/10.3390/agriculture14101783>
11. JASP Team. JASP (Version 0.16.2)[Computer software], 2022.
12. Li R., Xu C., Wu Z., Xu Y., Sun S., Song W., Wu C. Optimizing canopy-spacing configuration increases soybean yield under high planting density. *The Crop Journal*, 2025, 13(1), 233-245. <https://doi.org/10.1016/j.cj.2024.12.005>
13. Ling M., Su X., Hu X., Zhang X., Gu Y., Liu Z., Xie J., Qiu L. Identification and utilization of the soybean plant height locus PH19-31. *Agronomy*, 2025, 15(6), 1316. <https://doi.org/10.3390/agronomy15061316>
14. Lu Z., Gao J., Wang Q., Ning Z., Tan X., Lei Y., Zhang J., Zou J., Wang L., Yang C., Yang W., Yang F. Light energy utilization and measurement methods in crop production. *Crop and Environment*, 2024, 3(2), 91-100. <https://doi.org/10.1016/j.crope.2024.02.003>
15. Madias A., Mauro G.D., Vitantonio-Mazzini L.N., Gambin B.L., Borrás L. Environment quality, sowing date, and genotype determine soybean yields in the Argentinean Gran Chaco. *European Journal of Agronomy*, 2021, 123, 126217. <https://doi.org/10.1016/j.eja.2020.126217>
16. Miao L., Wang X., Yu C., Ye C., Yan Y., Wang H. What factors control plant height? *Journal of Integrative Agriculture*, 2024, 23(6), 1803-1824. <https://doi.org/10.1016/j.jia.2024.03.058>
17. Monfort M., Buitink J., Roeber F., Nogué F. Genome editing, an opportunity to revive soybean cultivation in Europe. *Plant Journal*, 2025, 121(4), e17266. <https://doi.org/10.1111/tjp.17266>
18. Nagashima H., Hikosaka K. Plants in a crowded stand regulate their height growth so as to maintain similar heights to neighbours even when they have potential advantages in height growth. *Annals of Botany*, 2011, 108(1), 207-214. <https://doi.org/10.1093/aob/mcr109>
19. Pagano M.C., Miransari M. 1 - The importance of soybean production worldwide. *Abiotic and Biotic Stresses in Soybean Production*, Soybean Production, 2016, 1, 1-26. <https://doi.org/10.1016/B978-0-12-801536-0.00001-3>
20. Peng H., Zhang Y., Nan T., Yang X., Pacenka S., Steenhuis T.S., Niu J. Climate change impacts on spatiotemporal variability of soybean water demands in North China Plain. *Agricultural Water Management*, 2025, 310, 109381. <https://doi.org/10.1016/j.agwat.2025.109381>
21. Peng Y., Zheng Y., Zheng Z., He Y. Evaluation and Optimization of Prediction Models for Crop Yield in Plant Factory. *Plants (Basel)*, 2025, 14(14), 2140. <https://doi.org/10.3390/plants14142140>
22. Popescu A., Dinu T.A., Stoian E., Șerban V., Hontus A., Angelescu C., Stanciu M. Soybean in the european union - an upward trend for cultivation and production. *Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development*, 2024, 25(2), 633-646.
23. Postma J.A., Hecht V.L., Hikosaka K., Nord E.A., Pons T.L., Poorter H. Dividing the pie: A quantitative review on plant density responses. *Plant, Cell & Environment*, 2021, 44(4), 1072-1094.

- <https://doi.org/10.1111/pce.13968>
24. Prusiński J., Nowicki R. Effect of planting density and row spacing on the yielding of soybean (*Glycine max* L. Merrill). Plant, Soil and Environment, 2020, 66(12), 616-623. <https://doi.org/10.17221/403/2020-PSE>
 25. Rotundo J.L., Marshall R., McCormick R., Truong S.K., Styles D., Gerde J.A., Gonzalez-Escobar E., Carmo-Silva E., Janes-Basset V., Logue J., Annicchiarico P., de Visser C., Dind A., Dodd I.C., Dye I., Long S.P., Lopes M.S., Pannecoucq J., Reckling M., Rushton J., Schmid N., Shield I., Signor M., Messina C.D., Rufino M.C. European soybean to benefit people and the environment. Scientific Reports, 2024, 14, 7612. <https://doi.org/10.1038/s41598-024-57522-z>
 26. Seo J., Park J., Choi M., Jung K., Chun H., Lee S., Gong D., Chae S.E., Jeon S.H., Yoon D.-K. Growth and yield response of soybean (*Glycine max* L.) in relation to sowing date in the Southern region of South Korea. Agronomy, 2024, 14, 2624. <https://doi.org/10.3390/agronomy14112624>
 27. Sun G., Zhang Y., Meng L., Liu Y., Wang L., Fei S., Che Y., Li Y., Qiu L., Lv C., Xu y., Ma Y. Field phenotyping for soybean density tolerance using time-series prediction and dynamic modeling. Plant Phenomics, 2025, 7(3), 100083. <https://doi.org/10.1016/j.plaphe.2025.100083>
 28. Thomasz E.O., Pérez-Franco I., García-García A. Assessing the impact of climate change on soybean production in Argentina. Climate Services, 2024, 34, 100458. <https://doi.org/10.1016/j.cliser.2024.100458>
 29. Vargas-Almendra A., Ruiz-Medrano R., Núñez-Muñoz L.A., Ramirez-Pool J.A., Calderón-Pérez B., Xoconostle-B., Cázares B. Advances in soybean genetic improvement. Plants, 2024, 13(21), 3073. <https://doi.org/10.3390/plants13213073>
 30. Wang L., Cheng B., Zhou T., Jing S., Liu R., Gao Y., Deng C., Ye W., Luo Z., Raza A., Xu M., Wang W., Liu W., Yang W. Quantifying the effects of plant density on soybean lodging resistance and growth dynamics in maize-soybean strip intercropping. Frontiers in Plant Science, (2023, 14, 1264378. <https://doi.org/10.3389/fpls.2023.1264378>
 31. Wolfram Research, Inc., Mathematica, Version 14.2, Champaign, IL (2024).
 32. Xiao S., Chen S.-Y., Zhao L.-Q., Wang G. Density effects on plant height growth and inequality in sunflower populations. Journal of Integrative Plant Biology, 48(5), 513-519. <https://doi.org/10.1111/j.1744-7909.2006.00265.x>
 33. Xu C., Li R., Song W., Wu T., Sun S., Han T., Wu C. High density and uniform plant distribution improve soybean yield by regulating population uniformity and canopy light interception. Agronomy, 2021, 11(9), 1880. <https://doi.org/10.3390/agronomy11091880>
 34. Xu N., Mao T., Zhang H., Huang X., Zhan Y., Liu J., Wang D., Zhai Y. Planting density and sowing date strongly influence canopy characteristics and seed yield of soybean in Southern Xinjiang. Agriculture, 2024, 14(11), 1892. <https://doi.org/10.3390/agriculture14111892>
 35. Yang Q., Lin G., Lv H., Wang C., Yang Y., Liao H. Environmental and genetic regulation of plant height in soybean. BMC Plant Biology, 2021, 21, 63. <https://doi.org/10.1186/s12870-021-02836-7>
 36. Yoshihira T., Suzuki H., Matsui T., Liang S., Shiraiwa T. Simplified estimation of branching plasticity of soybean cultivars in relation to planting density by branch development in the row with the gradient of distance between plants and after pinching. Plant Production Science, 2023, 26(2), 116-130. <https://doi.org/10.1080/1343943X.2023.2186900>
 37. Zhao J., Wang Y., Zhao M., Rodriguez D., de Voil P., Tan Z., Chu Q. Anticipated changes in soybean drought stress and yield stability under future climates in Northeast China. npj Sustainable Agriculture, 2025, 3, 14. <https://doi.org/10.1038/s44264-025-00053-5>
 38. Zhong Y.T., Zhong S.L. Advances in agronomic practices for high-yield soybean cultivation. Bioscience Methods, 2024, 15(6), 337-347.