Trends in Agricultural and Environmental Sciences
Pantanal Editora
10.46420/TAES.e240011

Sowing times of soybean cultivars in the southern region of Maranhão

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Received: 2024-07-03
Accepted: 2024-07-22
Published: 2024-08-12

Main Editor
Bruno Rodrigues de Oliveira

For citation: Zuffo, A. M.; Aguilera, J. G.; Steiner, F; Silva, F. C.; Mezzomo, R; Zanatta, T. S.; Barrozo, L. M.; Santos, J. C.; Coelho, Y. P.; Ratke, R. F. (2024). Sowing times of soybean cultivars in the southern region of Maranhão. Trends in Agricultural and Environmental Sciences, (e240011), DOI: 10.46420/TAES.e240011

Abstract: The sowing time and identification of soybean cultivars with the greatest productive potential in each growing region are crucial factors for maximizing the yield and profitability of crops. This study evaluated the effect of sowing time on the agronomic performance of 40 soybean cultivars and identified the best soybean cultivars to be recommended at each sowing time for the southern region of Maranhão. The field experiment consisted of two sowing times [soybean sown on November 10th, 2023 (1st sowing time) and December 2nd, 2023 (2nd sowing time)] and 40 soybean cultivars arranged in a split-plot experimental design with three replications. The results showed that sowing time and soybean cultivar differed in terms of grain yield potential. Compared with those sown in the first half of November, soybean cultivars sown at the beginning of December exhibit greater agronomic performance. The soybean cultivars BMX Olimpo IPRO, Latitude ADAPTA IPRO, 98R30 CE, BMX Fortaleza IPRO and M 8330 i2X have greater grain production potential when sown in the first half of November. The soybean cultivars SOY AMPLA IPRO, HO Coxim IPRO, DM 74K75 CE, FT® 3868 IPRO, DM 79I81 IPRO and M 8606 i2X have greater grain production potential when sown at the beginning of December.

Keywords: *Glycine max*; grain yield; phenotyping; soybean sowing window.

1. Introduction

Soybean [*Glycine max* (L.) Merrill.] is one of the most important oil crops in the world and is an excellent source of protein and edible oil. Soybean crops are widely cultivated in the Midwest, South and Southeast Brazil regions; however, their cultivation has been expanding rapidly to the northeast region of the country, including Maranhão, Tocantins, Piauí and Bahia. These states currently constitute the new Brazilian agricultural frontier. The state of Maranhão stands out as one of the new soybean production centers. In the 2023/2024 season, Brazil planted approximately 45.1 million hectares, obtaining an average grain productivity of 3,314 kg ha^{-1} (CONAB, 2024). The state of Maranhão currently represents almost 3% of the national soybean area, with an average grain yield of 3,268 kg ha^{-1}. Among the main challenges for soybean cultivation in the state of Maranhão, we highlight the sowing time and the choice of cultivars with greater production stability. These factors have a direct impact on grain yield and the profitability of soybean production systems in the state.

Soybean is a short-day species that depends on temperature and photoperiod for its adequate growth and development. These two factors have a direct impact on the duration of the soybean development cycle and delimit the appropriate geographic regions for its cultivation (Cai et al., 2020). Furthermore, the rate of rainfall after sowing and during crop flowering is another crucial factor that can influence the soybean development cycle. Therefore, the production of this oilseed crop is significantly affected by the interaction between the genotype, environmental conditions and management practices (Silva et al., 2019). Thus, identifying soybean cultivars adapted to each agricultural production region and determining the ideal time for sowing are among the most critical management strategies for ensuring the success of soybean crops (Guimarães et al., 2008).

Studies carried out in the Cerrado region with different soybean cultivars and sowing times have been reported to be extremely important for maximizing grain yield and crop profitability (Hackenhaar et al., 2019; Bossolani et al., 2022). The specific conditions of the Cerrado, which include a pronounced dry season and wide temperature range, have made it difficult to choose the best cultivars and sowing time for the different regions of the Brazilian Cerrado. Furthermore, in Brazil, there are approximately 2,379 soybean genetic materials registered with the National Cultivar Protection Service of the Ministry of Agriculture, Livestock and Supply (MAPA, 2024), which demonstrates that there are numerous options for choosing cultivars for the different Brazilian regions.

New soybean cultivars are cultivated annually in Brazil with the aim of enhancing productivity, resistance to diseases, tolerance to abiotic stresses such as drought and high temperatures, and adaptation to different climatic and soil conditions. Therefore, quantifying the grain yield potential of these new soybean cultivars in each of the Cerrado regions is important for boosting agricultural production of this oilseed crop in Brazil.

In this context, the sowing time and the choice of soybean cultivar are crucial factors for maximizing the yield and profitability of crops. These aspects depend on a series of factors, including climatic conditions, location of the cultivation region in relation to the equator and intrinsic characteristics of each genetic material, such as the development cycle and resistance to pests and diseases.

This study evaluated the effect of sowing time on the agronomic performance of 40 soybean cultivars and identified the best soybean cultivars to be recommended at each sowing time for the southern region of Maranhão.

2. Materials and Methods

2.1 Experimental area description

The field experiment was conducted at the Accert PCA Experimental Station located in the municipality of Balsas, MA (07°31'57" S, 46°02'08" W and altitude of 283 m), during the 2022/2023 agricultural season. The region's climate, according to Köppen's classification, is hot and humid tropical (Aw), with rainy summers and dry winters (Maranhão, 2002). The annual rainfall is approximately 1,175 mm (Passos et al., 2017). The rainfall data collected during the development of the soybean cultivars are shown in Figure 1.

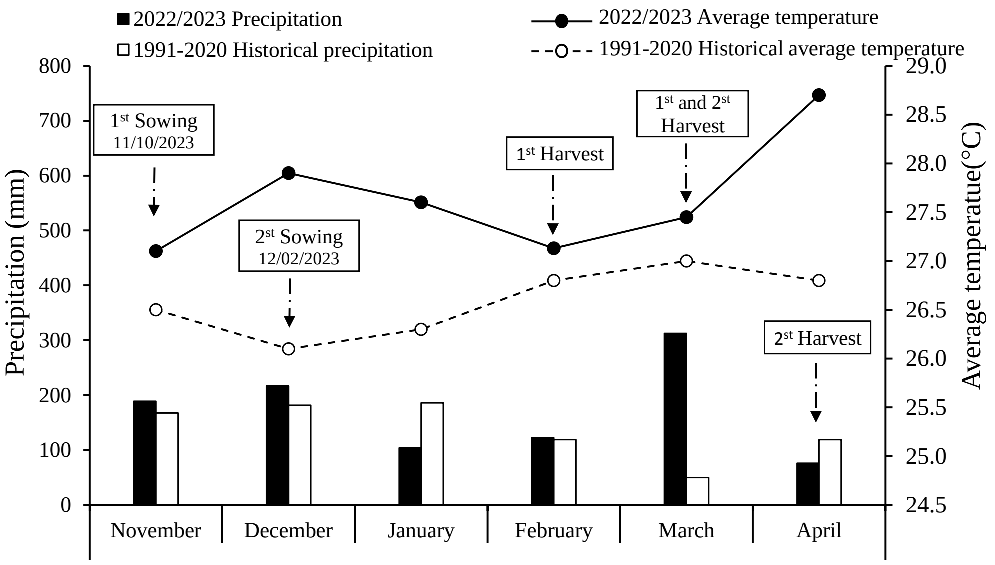

Figure 1. Monthly total precipitation (bars) and monthly average temperature (lines) in Balsas, Maranhão, Brazil, during the cultivation of soybean cultivars in the 2022/2023 season and 30 years of historical average data (1991 to 2020). Source: Accert CPA (2023) and National Meteorological Institute (2023).

The soil in the experimental area was classified as a sandy clay loam Oxisol (Latossolo Vermelho-Amarelo in the Brazilian classification) (Santos et al., 2018). Before starting the experiment, the soil was sampled for chemical and particle size analysis down to 0.40 m (Table 1).

Table 1. Soil chemical properties and particle size in the 0.0–0.20 and 0.20–0.40 cm layers at the beginning of the experiment

Depth	pH	O.M.	$P_{Mehlich-1}$	H+Al	Ca	Mg	K	CEC	V
(m)		g kg^{-1}	mg dm^{-3}	---------------- cmol$_c$ dm^{-3} -----------------					%
0.0–0.20	6.0	12.9	55.0	1.20	2.15	0.71	0.35	4.41	73
0.20–0.40	4.7	2.3	20.7	1.80	0.95	0.30	0.18	3.23	44
Depth	$S-SO_4$	Micronutrient					Particle size		
		B	Cu	Fe	Mn	Zn	Clay	Silt	Sand
(m)	---------------- mg dm^{-3} -----------------						---------- g kg^{-1} ----------		
0.0–0.20	6.30	0.22	0.44	113.21	14.28	0.73	242	93	665
0.20–0.40	12.60	0.23	0.40	81.98	4.25	0.37	–	–	–

pH in water. OM: organic matter. CEC: cation exchange capacity at pH 7.0. V: soil base saturation.

2.2 Experimental design and treatments

The study consisted of two sowing times [soybean sown on November 10th, 2023 (1st sowing time) and December 2nd, 2023 (2nd sowing time)] and 40 soybean cultivars arranged in a split-plot experimental design. The treatments were arranged in a randomized complete block design with three replications. The two sowing times were whole plots, and forty soybean cultivars (Table 2) were applied in subplots. The 1st and 2nd sowing times were in the middle and at the end of the optimal sowing window of the soybean crop to the southern region of the state of Maranhão, respectively. A total of 240 plots, 4.0 m wide × 10.0 m long, composed the entire study area. The useful area comprised the four central rows of each subplot, disregarding 1.0 m of each edge (i.e., 16 m^2).

2.3 Sowing, fertilization and management of soybean crops

Soybean cultivars were mechanically sown on November 10th, 2023, and December 2nd, 2023, in 0.50 m-spaced rows using the recommended seed density for each soybean cultivar (Table 2). At 15 days before soybean sowing, the weeds were desiccated with glyphosate (1.2 kg ha^{-1} a.i.) and haloxifope-p-methyl (60 g ha^{-1} a.i.) at a spray volume of 200 L ha^{-1}.

Table 2. Description and agronomic characteristics of the soybean cultivars used in the study.

Nº	Cultivars	Agronomic characteristics		Plant population	
		RMG	GT	Seeds per meter	Plants per hectare
1	NEO 760 CE	7.6	Indeterminate	20	400,000
2	Ellas MANU IPRO	7.6	Indeterminate	14	280,000
3	HO Guaporé i2X	7.7	Indeterminate	18	360,000
4	NK 7777 IPRO	7.7	Indeterminate	17	340,000
5	SOY AMPLA IPRO	7.9	Indeterminate	19	380,000
6	Latitude EVOLUI IPRO	7.9	Indeterminate	16	305,000
7	BMX Bônus IPRO	7.9	Indeterminate	16	320,000
8	97Y97 IPRO	7.9	Determinate	19	380,000
9	BMX Olimpo IPRO	8.0	Indeterminate	16	320,000
10	Ellas LYNDA IPRO	8.0	Indeterminate	11	220,000
11	NK 8100 IPRO	8.1	Indeterminate	16	320,000
12	HO Coxim IPRO	8.2	Indeterminate	15	300,000
13	DM 83IX84 i2X	8.3	Indeterminate	15	300,000
14	Latitude ADAPTA IPRO	8.4	Indeterminate	13	260,000
15	98R30 CE	8.3	Indeterminate	20	400,000
16	BMX Fortaleza IPRO	8.3	Indeterminate	13	260,000
17	M 8330 i2X	8.3	Determinate	14	280,000
18	Ellas SUZY IPRO	8.3	Indeterminate	11	220,000
19	TMG 22X83 i2X	8.3	Semideterminate	14	280,000
20	Latitude EXPANDE IPRO	8.3	Indeterminate	14	280,000
21	Latitude FORTALECE RR	8.3	Indeterminate	14	280,000
22	96R29 IPRO	6.2	Indeterminate	22	438,000
23	DM 74K75 CE	7.4	Indeterminate	20	400,000
24	FT® 3868 IPRO	7.6	Indeterminate	15	300,000
25	GNS 7700 IPRO	7.7	Indeterminate	18	360,000
26	Ellas ELISA IPRO	7.7	Indeterminate	13	260,000
27	DM 79I81 IPRO	7.9	Indeterminate	14	280,000
28	NEO 790 IPRO	7.9	Indeterminate	19	380,000
29	Ellas PAULA IPRO	7.9	Indeterminate	14	280,000
30	FT® 3190 IPRO	9.0	Determinate	12.5	250,000
31	Latitude AVANÇA IPRO	8.0	Indeterminate	17	325,000
32	FT® 4280 IPRO	8.0	Indeterminate	11	220,000
33	BMX Ataque i2X	8.1	Indeterminate	14	280,000
34	SYN 2282 IPRO	8.2	Semideterminate	18	360,000
35	DM 82I78 IPRO	8.2	Indeterminate	18	360,000
36	M 8644 IPRO	8.6	Determinate	11	220,000
37	M 8606 i2X	8.6	Determinate	10	200,000
38	NK 8770 IPRO	8.7	Semideterminate	16	320,000
39	FT® 4288 IPRO	8.8	Determinate	11	220,000
40	FT® 3179 IPRO	7.9	Indeterminate	15	300,000

RMG: Relative maturation group. GT: Growth type.

Base fertilization was carried out by applying 104 kg ha^{-1} P_2O_5 and 22 kg ha^{-1} N (monoammonium phosphate - MAP) to the sowing furrow. At 30 days after sowing [V_4 stage - four fully expanded leaves (fourth trifoliolate)], 120 kg ha^{-1} K_2O (KCl) was applied in the topdressing.

All soybean seeds used in the experiment were previously inoculated with efficient *Bradyrhizobium* spp. strains. The commercial liquid inoculants Simbiose Nod Soja (Simbiose: Biological Agrotechnology), containing the *Bradyrhizobium japonicum* strains [CPAC-15 (SEMIA 5079)] and *Bradyrhizobium diazoefficiens* strains [CPAC-7 (SEMIA 5080)] (minimum concentration of 7.2×10^9 viable cells/mL), were used at a rate of 3.0 mL kg^{-1} seed, as recommended by the manufacturer.

During the field experiments, the following products were used for weeds, pests and diseases: glyphosate, haloxifope-p-methyl, piraclostrobin + epoxyconazole, picoxistrobin + benzovindiflup, lancozeb, azoxistrobin + cipoconazole, teflubenzosan, chlorpirifos, cypermine and imidacloprid + beta-ciflutrin.

2.4 Measurement of the grain yield and production components

At full maturity (R_8 stage), the production components [plant height (PH), first pod insertion height (FPH), number of stems per plant (NSP), number of pods per plant (NPP), number of grains per pod (NGP), number of grains per plant (GP), and 1000-grain mass (1000-G)] and grain yield were determined. The production components were measured in ten randomly collected plants from each subplot. The pH (cm) was measured from the soil surface to the apical meristem of the plants using a tape measure. The FPH (cm) was determined from the soil surface to the insertion of the first pod using a tape measure. The mass of one thousand grains (g) was determined by the average of five measurements of 100 grains taken at random. The grains were weighed, and the grain yield (kg ha^{-1}) was calculated after the grain moisture content was corrected to 13%.

2.5 Statistical analyses

The data were subjected to analysis of variance (ANOVA) following the statistical model of the split-split plot (SSP) and randomized complete block design (RCBD). The means of the soybean cultivars were compared by the Scott–Knott test at the 0.05 level of confidence. Analysis of canonical variables was used to study the interrelationship between sets (vectors) of independent (sowing time and soybean cultivars) and dependent (grain yield and production components) variables. These analyses were performed using RBio software version 166 for Windows (Rbio Software, UFV, Viçosa, MG, BRA).

3. Results

Soybeans have been responsive to climate changes that occur in the different growing regions of this oilseed crop. Therefore, establishing the impact between sowing times and soybean genotypes cultivated in the Northeast Region of Brazil is important. The results of the analysis of variance showed that there was a significant interaction ($p < 0.001$) between soybean cultivar and sowing time for all agronomic traits and grain yield of the soybean crop (Table 3). A coefficient of variation (CV) below 35% was considered suitable for field experiments, which shows the precision of the experimental data.

Table 3. Summary of the analysis of variance for the agronomic traits of the 40 soybean cultivars in response to sowing times in the southern region of Maranhão.

Sources of variation	Probability > F							
	PH	FPH	NPP	NG	NGP	NSP	1000-G	GY
Cultivar (C)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sowing time (S)	<0.001	<0.001	0.949	0.826	0.030	<0.001	<0.001	0.144
C × S	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CV (%)	5.33	10.61	31.20	31.44	15.57	13.39	2.99	3.53

Plant height (PH), first pod insertion height (FPH), number of pods per plant (NPP), number of grains per plant (NGP), number of grains per pod (GP), number of stems per plant (NSP), 1000-grain mass (1000-G), and grain yield (GY) were measured. CV: Coefficient of variation.

Plant height allowed the soybean cultivars to be separated into six groups at the two sowing times. In the first sowing season, the group with taller plants was represented by the BMX Olimpo IPRO cultivar (87.4 cm), while the groups represented by the HO Guaporé i2X (54.0 cm), 97Y97 IPRO (53.3 cm), HO Coxim IPRO (56.3 cm), Latitude ADAPTA IPRO (57.7 cm), NEO 790 IPRO (53.5 cm) and Latitude AVANÇA IPRO (53.7 cm) cultivars had shorter plants. At the second sowing, the group with taller plants was represented by the DM 82I78 IPRO (87.3 cm), NK 8770 IPRO (89.6 cm) and FT® 4288 IPRO (88.3 cm) cultivars, while the group represented by the HO Guaporé i2X cultivar (48.0 cm) had shorter plants (Table 4). Considering sowing times, 22.5% of the soybean cultivars had greater plant heights when sown in the first season in November, while 42.5% of the cultivars had greater plant heights when sown in the second season in December. In turn, 35% of the soybean cultivars had similar plant heights, regardless of the sowing time (Table 4).

The insertion height of the first pod allowed the separation of the soybean cultivars into three and six groups when sown during the first or second sowing, respectively (Table 4). In the first sowing season, the group of plants with the highest insertion height of the first pod was represented by the cultivar BMX Olimpo IPRO (24.5 cm), while the group represented by 15 cultivars had plants with a lower insertion height of the first pod (13.2 to 16 cm). In the second sowing season, the cultivars DM 82I78 IPRO (20.9 cm) and BMX Ataque i2X (20.6 cm) represented the plant group with the greatest insertion height of the first pod. In turn, the group of plants with the lowest first pod insertion height was represented by 6 soybean cultivars whose first pod height varied from 7.9 to 11.0 cm (Table 4). Considering sowing times, 47.5% of the soybean cultivars had a greater first pod insertion height when sown in the first crop in November, while 12.5% of the cultivars had a greater first pod insertion height when sown in the second season in December. In turn, 40% of the soybean cultivars had no change in the height of the first pod due to the sowing time (Table 4).

The number of pods per plant allowed the separation of soybean cultivars into four and five groups when sown during the first or second sowing, respectively (Table 4). In the first sowing season, the group of plants with the greatest number of pods per plant was represented by the cultivars NEO 760 CE (100.2 pods), DM 83IX84 i2X (97.8 pods), Ellas SUZY IPRO (94.3 pods) and Ellas MANU IPRO (87.8 pods), while the group represented by 16 cultivars had plants with fewer pods (33.4 to 46.9 pods). In the second sowing season, cultivar HO Coxim IPRO (112.3 pods) represented the plant group with the greatest number of pods per plant. In turn, the group of plants with the lowest number of pods per plant was represented by 13 soybean cultivars whose number of pods varied from 27.8 to 46.3 (Table 4). Considering sowing times, 30% of the soybean cultivars had a greater number of pods per plant when sown in the first season in November, while 35% of the cultivars had a greater number of pods per plant when sown in the second season in December. In turn, 35% of the soybean cultivars had no change in the number of pods per plant due to the sowing time (Table 4).

Table 4. Plant height (PH), first pod insertion height (FPH), number of pods per plant (NPP) and number of grains per plant (GP) of the 40 soybean cultivars sown in two sowing seasons in the southern region of the state of Maranhão. Balsas, MA, Brazil.

Soybean cultivar	PH (cm)		FPH (cm)		NPP		GP	
	1ST†	2ST††	1ST†	2ST††	1ST†	2ST††	1ST†	2ST††
NEO 760 CE	60.3 e	74.1 c*	15.3 c	14.6 d	100.2 a	53.1 d*	192 a	133 c
Ellas MANU IPRO	80.5 b	74.1 c*	18.2 b	14.6 d*	87.8 a	53.1 d*	154 b	133 c
HO Guaporé i2X	54.0 f	48.0 f*	16.5 b	9.7 f*	71.7 b	27.8 e*	173 b	57 c*
NK 7777 IPRO	60.5 e	67.2 d*	16.7 b	10.1 f*	75.1 b	45.3 e*	223 a	294 a*
SOY AMPLA IPRO	58.9 e	79.4 c*	18.9 b	18.4 b	51.2 c	53.2 d*	96 c	112 c
Latitude EVOLUI IPRO	64.5 e	78.1 c*	17.2 b	16.5 c	74.3 b	53.1 d*	161 b	148 c
BMX Bônus IPRO	67.9 d	78.2 c*	16.6 b	13.5 e*	64.5 b	42.9 e*	208 a	86 c*
97Y97 IPRO	53.3 f	78.1 c*	17.2 b	17.3 b	59.1 c	45.1 e*	159 b	87 c*
BMX Olimpo IPRO	87.4 a	75.3 c*	24.5 a	14.2 d*	67.8 b	40.3 e*	175 b	95 c*
Ellas LYNDA IPRO	60.3 e	63.7 e	18.1 b	14.7 d*	52.9 c	46.3 e	117 c	91 c
NK 8100 IPRO	80.6 b	74.5 c*	17.7 b	18.1 b	70.1 b	98.2 b*	170 b	169 b
HO Coxim IPRO	56.3 f	68.7 d*	15.1 c	13.9 d	75.9 b	112.3 a*	188 a	217 b
DM 83IX84 i2X	71.9 d	81.8 b*	16.0 c	17.5 b	97.8 a	45.6 e*	210 a	64 c*
Latitude ADAPTA IPRO	57.7 f	59.5 e	17.8 b	10.5 f*	56.8 c	53.0 d	123 c	124 c
98R30 CE	74.3 c	72.7 c	17.5 b	14.3 d*	64.0 b	89.5 b*	155 b	187 b
BMX Fortaleza IPRO	75.6 c	66.1 d*	17.1 b	12.7 e*	75.0 b	52.5 d*	203 a	112 c*
M 8330 i2X	69.3 d	60.7 e*	17.3 b	11.5 e*	49.8 c	61.7 d	147 b	138 c
Ellas SUZY IPRO	68.1 d	70.5 d	14.9 c	14.5 d	94.3 a	55.3 d*	220 a	97 c*
TMG 22X83 i2X	69.1 d	62.3 e*	16.2 b	11.0 f*	37.5 d	70.1 c*	87 c	102 c
Latitude EXPANDE IPRO	66.4 d	65.8 d	17.8 b	14.0 d*	34.3 d	61.1 d*	83 c	136 c
Latitude FORTALECE RR	71.7 d	62.1 e*	17.7 b	15.3 d*	46.9 d	44.5 e	115 c	101 c
96R29 IPRO	66.2 d	63.5 e	16.3 b	14.9 d	38.7 d	46.1 e	96 c	109 c
DM 74K75 CE	68.9 e	75.5 c*	15.6 c	14.6 d	62.3 b	53.6 d	156 b	109 c
FT® 3868 IPRO	69.3 d	77.3 c*	16.4 b	16.4 c	51.1 c	38.6 e	128 c	90 c
GNS 7700 IPRO	67.2 d	75.1 c*	14.1 c	16.8 c*	43.9 d	50.8 d	105 c	129 c
Ellas ELISA IPRO	76.1 c	70.8 d*	17.9 b	15.7 c	45.9 d	43.9 e	93 c	116 c
DM 79I81 IPRO	64.7 e	67.3 d	15.5 c	9.7 f*	64.4 b	62.0 d	151 b	152 c
NEO 790 IPRO	53.5 f	63.9 e*	17.0 b	14.6 d*	33.4 d	71.1 c*	71 c	193 b*
Ellas PAULA IPRO	68.8 d	72.5 c	16.4 b	10.5 f*	45.5 d	77.7 c*	92 c	137 c
FT® 3190 IPRO	63.8 e	74.7 c*	14.3 c	12.9 e	72.4 b	51.5 d*	159 b	96 c*
Latitude AVANÇA IPRO	53.7 f	68.9 d*	13.8 c	14.9 d	43.3 d	45.0 e	97 c	103 c
FT® 4280 IPRO	66.1 d	66.3 d	17.1 b	13.1 e*	53.4 c	57.5 d	99 c	111 c
BMX Ataque i2X	69.3 d	71.3 d	16.7 b	20.6 a*	44.5 d	70.0 c*	95 c	161 c*
SYN 2282 IPRO	58.4 e	64.6 e*	14.4 c	17.7 b*	43.5 d	69.9 c*	100 c	143 c
DM 82I78 IPRO	58.9 e	87.3 a*	14.6 c	20.9 a*	42.3 d	92.9 b*	105 c	180 b*
M 8644 IPRO	68.6 d	61.9 e*	17.3 b	10.8 f*	46.5 d	36.4 e	74 c	90 c
M 8606 i2X	65.9 d	69.5 d	14.1 c	7.9 f*	56.2 c	97.6 b*	132 c	300 a*
NK 8770 IPRO	61.7 e	89.6 a*	14.9 c	16.3 c	44.5 d	70.9 c*	118 c	151 c
FT® 4288 IPRO	62.5 e	88.3 a*	15.5 c	16.3 c	43.9 d	75.7 c*	110 c	139 c
FT® 3179 IPRO	67.3 d	62.6 e	13.2 c	16.3 c*	36.0 d	93.1 b*	70 c	207 b*

Knott test at the 0.05 level of confidence. Asterisks indicate a significant difference (F test; p < .05) between the two sowing seasons for each soybean cultivar. † 1ST: 1st sowing time (soybean sown on November 10th, 2023). †† 2ST: 2nd sowing time (soybean sown on December 2nd, 2023).

The number of grains per plant allowed the separation of soybean cultivars into three groups at both sowing times (Table 4). In the first sowing season, the group of plants with the greatest number of grains per plant was represented by the cultivars NK 7777 IPRO (223 grains), Ellas SUZY IPRO (221 grains), DM 83IX84 i2X (210 grains), BMX Bônus IPRO (208 grains), BMX Fortaleza IPRO (203 grains), NEO 760 CE (192 grains) and HO Coxim IPRO (188 grains), while the group represented by 22 cultivars had plants with a lower number of pods per plant (70 to 132 grains). In the second sowing season, cultivars M 8606 i2X (300 grains) and NK 7777 IPRO (294 grains) represented the plant group with the greatest number of grains per plant. In turn, the group of plants with the lowest number of grains per plant was represented by 19 soybean cultivars whose number of grains per plant varied from 57 to 116 (Table 4). Considering sowing times, 20% of the soybean cultivars had a greater number of grains per plant when sown in the first season in November, while 15% of the cultivars had a greater number of grains per plant when sown in the second season in December. In turn, 65% of the soybean cultivars showed no change in the number of grains per plant due to the sowing time (Table 4).

The number of grains per pod grouped the 40 soybean cultivars into the same group in the first sowing season and allowed the cultivars to be separated into two groups in the second sowing season (Table 5). In the second sowing season, the cultivar NK 7777 IPRO (3.4 grains) represented the plant group with the greatest number of grains per pod, while the other cultivars had between 1.4 and 3.0 grains per pod. Considering the sowing times, only the cultivar NK 7777 IPRO had a change in the number of grains per pod due to the sowing time (Table 5).

The number of stems per plant allowed the separation of soybean cultivars into eight and five groups when sown in the first or second sowing time, respectively (Table 5). In the first sowing season, the group of plants with the greatest number of stems per plant was represented by the cultivar NK 7777 IPRO (8.1 stems), while the group represented by the cultivars Ellas LYNDA IPRO (2.9 stems), FT® 3179 IPRO (2.8 stems) and M 8606 i2X (2.5 stems) had plants with a lower number of stems per plant (Table 5). In the second sowing season, the cultivar NK 8100 IPRO (6.7 stems) represented the plant group with the greatest number of stems per plant. In turn, the group of plants with the lowest number of stems per plant was represented by 8 soybean cultivars whose number of stems varied from 1.5 to 2.4 (Table 5). Considering sowing times, 67.5% of soybean cultivars had a greater number of stems per plant when sown in the first season in November, while 5.0% of cultivars had a greater number of stems per plant when sown in the second season in December. In turn, 27.5% of the soybean cultivars did not change the number of stems per plant due to the sowing time (Table 5).

The 1000-grain mass allowed the separation of soybean cultivars into eight and seven groups when sown during the first or second sowing, respectively (Table 5). In the first sowing season, the group of plants with the highest mass of one thousand grains was represented by the cultivar Latitude AVANÇA IPRO (205 g), while the group represented by the cultivars BMX Ataque i2X (139 g), GNS 7700 IPRO (137 g), FT® 3179 IPRO (132 g) and BMX Fortaleza IPRO (131 g) had plants with a lower mass of one thousand grains (Table 5). In the second sowing season, the cultivars BMX Bônus IPRO (208 g), Latitude AVANÇA IPRO (203 g), SYN 2282 IPRO (202 g), NK 8100 IPRO (200 g) and Ellas LYNDA IPRO (200 g) represented the plant group with the highest mass of one thousand grains. The group of plants with the lowest 1000-grain mass was represented by the soybean cultivars FT® 4288 IPRO (139 g) and BMX Fortaleza IPRO (132 g) (Table 5). Considering the sowing times, only 2.5% of the soybean cultivars had a greater 1000-grain mass when sown in the first season in November, while 72.5% of the cultivars had a greater 1000-grain mass when sown in the second season in December. In turn, the mass of one thousand grains did not change for 25% of the soybean cultivars due to the sowing time (Table 5).

The grain yield allowed the separation of soybean cultivars into ten and eight groups when sown in the first or second sowing time, respectively (Table 5). In the first sowing season, the group of plants with the highest grain yield was represented by the cultivar 98R30 CE (4,748 kg ha^{-1}) and Latitude ADAPTA IPRO (4,586 kg ha^{-1}), while the group represented by the cultivar 96R29 IPRO (1,854 kg ha^{-1}) had plants with a lower grain yield (Table 5). In the second sowing season, the cultivar DM 79I81 IPRO (4,097 kg ha^{-1}) represented the plant group with the highest grain yield. In turn, the group with the lowest grain yield was represented by soybean cultivars 96R29 IPRO (2,724 kg ha^{-1}) and BMX Bônus IPRO (2,678 kg ha^{-1}) (Table 5). With respect to sowing time, 35% of the soybean cultivars had greater grain yields when sown in the first season in November, while 45% of the cultivars had greater grain yields when sown in the second season in December. In turn, 20% of the soybean cultivars exhibited no change in grain yield due to the sowing time (Table 5).

Table 5. Number of grains per pod (NGP), number of stems per plant (NSP), and 1000-grain mass (1000-G)] and grain yield of the 40 soybean cultivars sown in two sowing seasons in the southern region of the state of Maranhão. Balsas, MA, Brazil.

Soybean cultivars	NGP		NSP		1000-G (g)		GY (kg ha^{-1})	
	1ST†	2ST††	1ST†	2ST††	1ST†	2ST††	1ST†	2ST††
NEO 760 CE	1.9 a	2.5 b	6.4 c	2.9 d*	148 g	161 e*	3,364 f	3,212 f
Ellas MANU IPRO	1.8 a	2.5 b	7.1 b	2.9 d*	150 f	166 d*	3,239 g	3,299 e
HO Guaporé i2X	2.4 a	2.0 b	7.1 b	1.5 e*	177 c	184 c*	3,608 e	3,582 c
NK 7777 IPRO	2.6 a	3.7 a*	8.1 a	1.9 e*	185 c	191 b	3,969 d	3,649 c*
SOY AMPLA IPRO	1.9 a	1.7 b	4.0 f	3.1 d*	162 e	182 c*	3,447 f	3,872 b*
Latitude EVOLUI IPRO	2.2 a	2.8 b	6.3 c	3.3 c*	165 e	174 d*	3,377 f	3,555 c*
BMX Bônus IPRO	2.2 a	2.1 b	6.0 d	1.9 e*	181 c	208 a*	3,603 e	2,678 h*
97Y97 IPRO	2.7 a	1.9 b	5.2 e	3.7 c*	169 d	179 c*	2,889 h	3,089 f*
BMX Olimpo IPRO	2.2 a	2.3 b	5.5 d	2.9 d*	183 c	195 b*	4,341 b	3,557 c*
Ellas LYNDA IPRO	2.2 a	2.0 b	2.9 h	3.8 c*	195 b	200 a	3,911 d	3,179 f*
NK 8100 IPRO	2.4 a	2.0 b	6.0 d	6.7 a	195 b	200 a	3,115 g	3,295 e*
HO Coxim IPRO	2.5 a	2.1 b	6.3 c	4.6 b*	190 b	198 b*	3,433 f	3,768 b*
DM 83IX84 i2X	2.2 a	1.4 b	5.9 d	3.5 c*	148 g	165 d*	4,115 c	3,542 c*
Latitude ADAPTA IPRO	2.2 a	2.3 b	5.4 e	2.9 d*	161 e	179 c*	4,586 a	2,908 g*
98R30 CE	2.4 a	2.4 b	6.6 c	3.4 c*	170 d	181 c*	4,748 a	3,182 f*
BMX Fortaleza IPRO	2.7 a	2.1 b	6.3 c	4.5 b*	131 h	132 g	4,363 b	3,440 d*
M 8330 i2X	3.3 a	2.2 b	4.5 f	3.9 c	149 g	156 e	4,393 b	3,420 d*
Ellas SUZY IPRO	2.4 a	1.8 b	5.7 d	3.0 d*	144 g	153 f*	3,893 d	3,675 c*
TMG 22X83 i2X	2.3 a	1.8 b	3.7 f	3.5 c	176 c	184 c*	3,856 d	3,358 e*
Latitude EXPANDE IPRO	2.4 a	2.2 b	4.2 f	3.4 c*	169 d	185 c*	3,327 f	3,581 c*
Latitude FORTALECE RR	2.5 a	1.8 b	3.3 g	1.5 e*	151 f	161 e*	4,185 c	3,376 e*
96R29 IPRO	2.5 a	2.4 b	4.4 f	2.9 d*	156 f	161 e	1,854 j	2,724 h*
DM 74K75 CE	2.5 a	2.1 b	4.9 e	3.7 c*	161 e	170 d*	2,899 h	3,851 b*
FT® 3868 IPRO	2.5 a	2.3 b	5.1 e	2.4 e*	147 g	162 e*	2,833 h	3,718 b*
GNS 7700 IPRO	2.4 a	2.5 b	3.9 f	2.3 e*	137 h	166 d*	2,829 h	3,195 f*
Ellas ELISA IPRO	2.0 a	2.6 b	4.2 f	3.4 c*	165 e	176 c*	3,017 h	3,672 c*
DM 79I81 IPRO	2.4 a	2.5 b	4.9 e	2.9 d*	180 c	197 b*	2,955 h	4,099 a*
NEO 790 IPRO	2.1 a	2.7 b	5.3 e	4.4 b*	145 g	191 b*	2,873 h	3,369 e*
Ellas PAULA IPRO	2.0 a	1.7 b	4.1 f	3.7 c	153 f	184 c*	3,544 e	3,451 d
FT® 3190 IPRO	2.2 a	1.9 b	4.9 e	1.9 e*	132 h	147 f*	2,403 i	3,048 f*
Latitude AVANÇA IPRO	2.2 a	2.3 b	3.5 g	2.0 e*	205 a	203 a	3,142 g	3,175 f
FT® 4280 IPRO	1.9 a	1.9 b	4.5 f	4.2 b	159 e	181 c*	3,109 g	3,187 f
BMX Ataque i2X	2.1 a	2.3 b	3.4 g	4.9 b*	139 h	159 e*	2,819 h	3,649 c*
SYN 2282 IPRO	2.3 a	2.0 b	3.4 g	3.8 c	177 c	202 a*	2,905 h	3,552 c*
DM 82I78 IPRO	2.5 a	1.9 b	3.7 f	4.5 b	147 g	169 d*	2,371 i	3,346 e*
M 8644 IPRO	1.8 a	2.5 b	3.4 g	3.0 d	151 f	161 e*	3,235 g	3,196 f
M 8606 i2X	2.4 a	3.0 b	2.5 h	4.4 b*	157 f	152 f	3,405 f	3,809 b*
NK 8770 IPRO	2.7 a	2.1 b	3.3 g	3.0 d	175 d	169 d	3,788 d	3,164 f*
FT® 4288 IPRO	2.5 a	1.8 b	3.9 f	3.7 c	152 f	139 g*	3,697 e	3,385 e*
FT® 3179 IPRO	2.0 a	2.2 b	2.8 h	3.2 d	157 f	154 f	3,699 e	3,541 c
Number of groups	1	2	8	5	8	7	10	8

Mean followed by distinct letters on the column for the soybean cultivars show significant differences by the Scott–Knott test at the 0.05 level of confidence. Asterisks show a significant difference (F test; p < .05) between the two sowing seasons for each soybean cultivar. † 1ST: 1st sowing time (soybean sown on November 10th, 2023). †† 2ST: 2nd sowing time (soybean sown on December 2th, 2023).

Canonical correlation analysis was performed between the agronomic traits and sowing times (Figure 2A) and among the 40 soybean cultivars (Figure 2B). These analyses showed that the canonical variables were able to explain 100% of the data variability when considering sowing times. The second sowing time was better than the first sowing time for most of the agronomic traits of the soybean cultivars, except for the first pod insertion height (FPH) and number of stems per plant (NSP) (Figure 2A). There was a wide dispersion of the 40 soybean cultivars, and the canonical correlation analysis was able to explain 71.9% of the data variability (Figure 2B). Among the agronomic traits, the greatest variability was obtained for 1000-grain mass and grain yield, which was also evidenced by the analysis of variance with the formation of a greater number of groups using the Scott–Knott test.

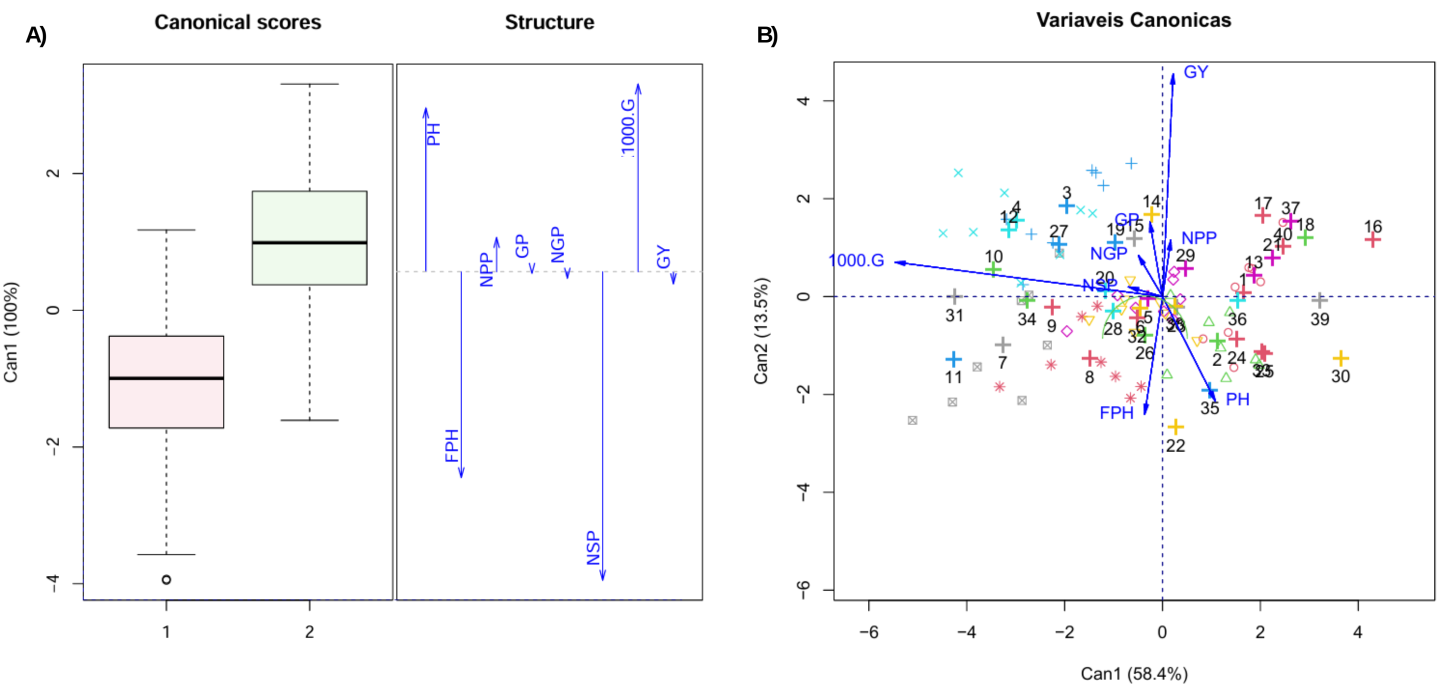

Figure 2. Canonical correlation analysis (CCA) between the agronomic traits and sowing times (A) and between the agronomic traits and soybean cultivars (B). The blue lines show the canonical correlation between the centroids of the first pair of canonical variates and the lineal tendency line. Abbreviations: PH: plant height. FPH: first pod insertion height. NPP: number of pods per plant. GP: number of grains per plant. NGP: number of grains per pod. NSP: number of stems per plant. 1000-G: 1000-grain mass. GY: grain yield.

4. Discussion

The agronomic performance of soybean cultivars sown two times was our main objective. This agronomic performance was measured through eight production components of the soybean crop using univariate analysis of variance (Tables 4 and 5) and multivariate canonical correlation analysis (Figure 2).

The sowing time and the choice of the best cultivar represent two of the main points to be considered when determining the maximum productive performance of modern soybean cultivars. The variability obtained within cultivars when sown at different times is a response associated with the interaction of the genotype with the environment (G × A). This interaction allows the choice of genotypes in different regions or sowing times, which has been reported in previous research (Hackenhaar et al., 2019; Bossolani et al., 2022).

G×E interaction studies are always proposed and help recommend cultivars that are better adapted and more responsive to environmental changes for different soybean production regions around the world (Valencia-Ramírez; Tibocha-Ardila, 2023; Mossie et al., 2024; Hyten et al., 2024; Van der Merwe et al., 2024) and Brazil (Oliveira et al., 2003; Silva& Duarte, 2006; Lima et al., 2008; Peluzio et al., 2012; Barros et al., 2012; Chagas et al., 2023; Neitzke et al., 2024). This sensitivity to climatic conditions not only influences the stages of plant development but also delimits the most appropriate regions for soybean cultivation (Silva et al., 2019). Therefore, selecting soybean cultivars that are well adapted to each region and determining the ideal time for sowing are among the most critical management strategies for ensuring successful soybean production (Guimarães et al., 2008).

The southern region of Maranhão, which is part of the Brazilian Cerrado Biome, has a well-defined dry season and experiences significant changes in environmental temperature. Therefore, choosing the appropriate sowing time and choosing the most productive cultivars for regional conditions directly affects grain yield, pest and disease management, and the efficiency of the use of water resources. The climatic conditions evidenced during soybean cultivation and based on historical data from the last 30 years (Figure 1) indicate that there are some variations related to the rainfall rate between the two sowing seasons used in this study [soybeans grown from October to March (1st sowing time) and soybeans grown from December to April (2nd sowing time)]. During the development cycle of soybean cultivars sown in the first season in November, there was a total rainfall accumulation of 945 mm, while during the development cycle of cultivars sown in the second season in December, there was a total accumulated rainfall of 832 mm (Figure 1). In general, a rainfall of 620 mm is considered ideal for the optimal development of soybean crops. Therefore, this variation of only 113 mm between the two soybean sowing times should not have significantly influenced the productive performance of the soybean cultivars.

Rainfall, as a limiting factor for water supply in rainfed conditions, needs to be adequately distributed during the crop development cycle and has been considered a limiting factor for the development and yield of soybean crops (Neumaier et al., 2003). The most critical phases of water demand are during germination and emergence and during flowering and grain filling, with a maximum water requirement occurring during flowering and grain filling (7 to 8 mm day^{-1}).

The results showed that the second soybean sowing time was responsible for the greatest increase in plant height, number of pods per plant, thousand grain mass and grain yield for most cultivars (Tables 4 and 5). In turn, the first sowing time resulted in the highest values for first pod insertion height and number of stems per plant for most soybean cultivars. Such evidence reports the complexity of the G×A interaction that results in different responses between soybean cultivars depending on the sowing time. Therefore, to improve the understanding of these responses, multivariate analyses are proposed and assist in decision making when recommending cultivars more adapted to the Brazilian Cerrado (Oliveira et al., 2003; Barros et al., 2012; Valencia-Ramírez & Tibocha-Ardila, 2023; Neitzke et al., 2024). In this context, the results of the canonical correlation analysis confirm that there is better productive performance of most soybean cultivars when they are sown in the second season in December (Figure 2A).

The insertion height of the first soybean pod is an important agronomic characteristic for mechanized soybean harvesting. According to Sediyama et al. (2015), the insertion height of the first pod must be at least 12.0 cm to reduce losses during mechanized harvesting operations. Therefore, based on this reference value, the insertion height of the first pod obtained in this study may be a limiting factor for mechanized harvesting only in nine soybean cultivars (HO Guaporé i2X, NK 7777 IPRO, Latitude ADAPTA IPRO, M 8330 i2X, TMG 22X83 i2X, DM 79I81 IPRO, Ellas PAULA IPRO, M 8644 IPRO and M 8606 i2X) sown at the end of the sowing window in December (Table 5).

5. Conclusion

The sowing time and soybean cultivar had different expression levels of grain yield potential.

Compared with those sown in the first half of November, soybean cultivars sown at the beginning of December exhibit greater agronomic performance.

The soybean cultivars BMX Olimpo IPRO, Latitude ADAPTA IPRO, 98R30 CE, BMX Fortaleza IPRO and M 8330 i2X have greater grain production potential when sown in the first half of November.

The soybean cultivars SOY AMPLA IPRO, HO Coxim IPRO, DM 74K75 CE, FT® 3868 IPRO, DM 79I81 IPRO and M 8606 i2X have greater grain production potential when sown at the beginning of December.

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7. Additional Information

7.1 Acknowledgments

The authors are grateful to "Accert Pesquisa e Consultoria Agronomia" for financial support with agricultural inputs and for providing the experimental area.

7.2 Funding

There was no funding for this research.

7.3 Conflicts of interest

The authors declare no conflicts of interest.