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SOWING AND TOPDRESSING-SPLIT DATES IN SECOND-CROP MAIZE GROWN IN THE CERRADO-AMAZON REGION

ABSTRACT – Corn must be sown for the second harvest in the Cerrado-Amazônia ecotone until approximately February 20th to avoid productivity losses due to the lack of rain that may occur in the reproductive stage. Often, producers delay sowing and the first fertilization application for weather or operational reasons and expose crops to water shortage. The current study aims to investigate maize yield and nutritional status at two sowing and topdressing management dates. The experiment was conducted in Santa Carmem municipality (MT). It followed a randomized block design, with five repetitions and factorial arrangement comprising ten application times of the 1stfertilizer dose (200 kg ha^{-1} of 20-00-20 formula), two maize sowing dates (01/19th and 02/27th), and the second fertilizer application fixed at 35 DAS (200 kg ha^{-1} of 20-00-20 formula). Maize sown in January recorded a higher yield rate than that sown at the end of the recommended period due to better water availability conditions, which led to more significant amounts of grains per year and higher-weight grains, resulting in a gain of 2.33 Mg ha^{-1}. Topdressing management has influenced nitrogen (N) and potassium (K) concentrations in leaves and grains and soil K content at the end of the cycle - soil recorded higher residual K content when maize was sown in January. Potassium (K) extraction from the soil to produce 1 ton of grains was higher in soil sown in late February. It happened due to the higher water stress the crop was exposed to, which required more K; both sowing dates recorded similar total K extraction values but different yield rates.
Keywords: topdressing, water shortage, late sowing

ÉPOCAS DE SEMEADURA E ADUBAÇÃO DE COBERTURA COM NITROGÊNIO E POTÁSSIO NA CULTURA DO MILHO SEGUNDA SAFRA NA REGIÃO DE TRANSIÇÃO CERRADO-AMAZÔNIA

RESUMO - A semeadura do milho 2ª safra de alto potencial produtivo no ecótono Cerrado-Amazônia deve ser realizada até o final do mês de fevereiro, para evitar perdas de produtividade pela falta de chuvas no estádio reprodutivo, tendo como limite aproximadamente o 20º dia do mês de fevereiro. Por motivos climáticos ou operacionais, muitas vezes o produtor atrasa a semeadura e a primeira adubação, expondo a lavoura a déficit hídrico. Objetivou-se verificar a produtividade do milho e seu estado nutricional em duas datas de semeio e manejo da adubação de cobertura. O experimento foi conduzido em Santa Carmem–MT, em delineamento experimental de blocos casualizados, com cinco repetições, em esquema fatorial, com 10 épocas de aplicação da 1ª parcela de adubação (200 kg ha^{-1}) do formulado 20-00-20, em 2 datas de semeadura do milho (19/01 e 27/02), e com a 2ª parcela fixa aos 35 DAS (200 kg ha^{-1} de 20-00-20). Verificou-se maior produtividade do milho semeado em janeiro em relação a semeadura no final da época recomendada, devido as condições hídricas mais favoráveis que culminaram na maior quantidade de grãos por espiga e grãos com maior massa, o que resultou num ganho de 2,33 Mg ha^{-1}. O manejo da adubação de cobertura influencia a concentração de N e K nas folhas, nos grãos e o teor de K no solo, ao final do ciclo, com maior teor de K residual quando o milho foi semeado em janeiro. A extração de K do solo para produzir uma tonelada de grãos foi superior para a semeadura no final de fevereiro, resultado do maior estresse hídrico que a cultura sofreu, demandando mais K; com extrações totais similares nas duas datas de semeadura e diferentes produtividades.
Palavras-chave: adubação de cobertura, déficit hídrico, semeadura tardia

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Second-crop maize yield (or milho safrinha, as it is called in Brazil) following soybean crops in the Brazilian Cerrado region, specifically Mato Grosso State (MT), has been increasing. It was at most 2.0 Mg ha^{-1} until the late 1990s, and it was grown for straw formation and soil cover purposes, based on low investment and low expectation of economic return. Currently, second-crop cultivation plays a vital role in the national scenario since it generates substantial income for producers, as well as several job positions in beneficiary companies, mainly in ethanol plants, which account for 11 units in Mato Grosso State, and whose production is expected to reach 4.16 billion liters in the 2023/24 crop. This state accounts for 80% of all maize ethanol produced in Brazil (MATO GROSSO, 2024).

Mean grain yield rates have significantly increased over the last 20 years. It rose from 2.72 Mg ha^{-1} in the 2001/2002 crop to 6.88 Mg ha^{-1} in the 2022/2023 crop (CONAB, 2024); commercial crops produced 11 Mg ha^{-1} and experimental results reached up to 14 Mg ha^{-1} (AGROCAMPO, 2024).

Currently, soybean harvesting in Northern Mato Grosso State (Cerrado-Amazon ecotone) occurs while maize is planted in January and February. Operations happening in each rural property - almost daily during this period - are split as follows: products' applications during the soybean maturation phase, desiccation, harvesting, maize sowing, and first fertilizer application, which is followed by spraying (all these procedures are performed within weeks). Some operations, such as fertilizer application in maize crops, do not occur on the most appropriate date in this context due to logistics issues and unfavorable weather conditions.

Fancelli (2008) assessed the best time for nitrogen fertilizer application in maize grown in different soil types and observed that sowing fertilization should be carried out with 30-50 kg ha^{-1} N. Topdressing in clayey soils can be performed at once, between stages V3 and V4 (fully developed leaves). On the other hand, according to the author, the ideal topdressing for sandy soils should be carried out in two applications: between V3-V4 and between V6-V8. The most recent published recommendation for nitrogen (N) and potassium (K) management in maize crops (which resulted from years of study and was reviewed by Duarte et al., 2022) takes into account the expected yield. Nitrogen doses recommended for yield expectations ranging from 6 to 10 Mg ha^{-1} (which is the condition observed in Mid-Northern Mato Grosso State) range from 90 to 120 kg ha^{-1}, whereas K doses recommended based on soil analysis results range from 30 to 100 kg ha^{-1} K_2O. Concerning N splitting, the authors above recommend applying from 30 to 60 kg ha^{-1} at sowing time and the rest as topdressing at doses lower than 80 kg ha^{-1} when maize has 4-5 leaves. As for higher N doses, they recommend splitting

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between maize, presenting 2-3 and 6-7 leaves. The potassium (K) dose should not exceed 50 kg ha^{-1} K_2O in the sowing furrow; the rest should be applied as topdressing. When the K dose applied in clayey soils is ≥80 kg ha^{-1} K_2O, it is recommended to transfer part of the fertilizer, or entirely, to pre-sowing through the broadcasting application (DUARTE et al., 2022).

This management system has been changing in recent years due to the appreciation of maize crops, which have been fertilized with P. Thus, farmers often use only N and K in maize crops at topdressing doses ranging from 60 to 100 kg ha^{-1}. These doses can change depending on the technological level of cultured materials and the sowing season.

Most producers split this fertilization process into two periods, from stage V1 to V8 or even later. The first application takes place from 3 to 15 days after sowing (DAS), depending on machinery availability and weather conditions, whereas the second application is performed between 25 and 35 DAS. However, the first topdressing fertilizer application may only sometimes occur at the ideal stage, mainly up to V4 (when potential production is defined), when plants mostly require nutrients due to operational issues.

Given this context and the scarcity of research results applicable to local conditions, it is possible to state that better sowing management and NK fertilizer application in second-crop maize, within the sowing window, in the Cerrado-Amazon transition region can benefit crops growing under higher rainfall. In addition, application time and topdressing fertilization splitting can interfere with nutrient absorption, export and cycling processes, and maize yield.

In light of the preceding, the current study aimed to investigate maize crop yield in two sowing seasons, the management of topdressing fertilization with N and K, the nutritional status of the crop, and soil fertility after maize harvest.

Materials and Methods

The experiment was conducted in 2018, with second-crop maize grown after soybean crop in São José Farm (Bedin Group), Santa Carmem municipality - MT (geographic coordinates 12°05'12.76" S and 54°56'19.16" W; altitude of 389 m). The climate in this region is classified as tropical rainy (type AW – Köopen's classification), with mean annual rainfall volume ranging from 1,800 to 2,000 mm $year^{-1}$ (SOUZA et al. 2013) and a well-defined dry season from May to September. The daily rainfall volumes were collected by a gauge installed in the investigated site (Figure 1).

The history of the investigated site before experiment installation shows that it was cleared of vegetation in 2005 and planted with upland rice in the following year. Since then, soybean/maize crops have been successively grown in it. This area's management is based on a high

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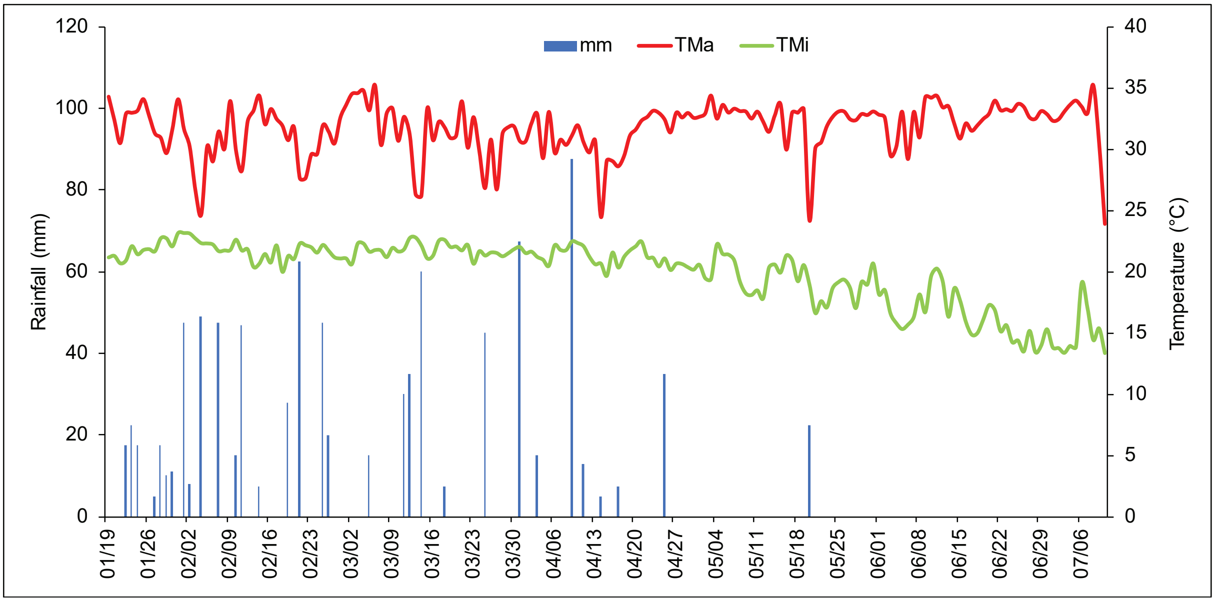

Figure 1. Data on daily rainfall collected at the experimental site and events observed from sowing to harvest. Maximum and minimum temperature data, EMBRAPA AGROSSILVIPASTORIL meteorological station (2024). Caption: **1** – Sowing 1st (01/19/2018), 2nd (02/27/2018); **2** – 3 DAS, 1st (01/22/2018), 2nd (03/02/2018); **3** – 6 DAS 1st (01/25/2018), 2nd (03/05/2018); **4** – 9 DAS 1st (01/28/2018), 2nd (03/08/2018); **5** – 12 DAS 1st (01/31/2018), 2nd (03/11/2018); **6** – 15 DAS 1st (02/03/2018), 2nd (03/14/2018); **7** – 18 DAS 1st (02/06/2018), 2nd (03/17/2018); **8** – 18 DAS 1st (02/09/2018), 2nd (03/20/2018); **9** – 35 DAS 1st (02/23/2018), 2nd (04/03/2018); **10** – Inflorescence 1st (03/12/2018), 2nd (04/13/2018).

technological production level, which leads to high yield rates.

The soil in this region is classified as yellow-red latosol of clay texture (EMBRAPA, 2013). Based on soil analysis, the experimental area was defined before soybean sowing (October 2017). Before experiment installation, soil chemical and physical analysis were applied to a sample collected from the 0-20 cm layer. The following results were observed: pH_{H2O} = 5.90; M.O. = 31 g kg^{-1}, P = 6.0 mg dm^{-3}, K = 114 mg dm^{-3}; Ca = 2.46 cmol$_c$ dm^{-3}; Mg = 0.82 cmol$_c$ dm^{-3}; H+Al = 3.1 cmol$_c$ dm^{-3}; CTC= 6.7 cmol$_c$ dm^{-3}; V = 53.2%, 475 g kg^{-1} clay, 75 g kg^{-1} silt and 450 g kg^{-1} sand.

The experiment followed a randomized block design, with five repetitions and a 10 x 2 factorial arrangement (Table 1). The first level consisted of 10 application times of the 20-00-20-09 formula (N-P_2O_5 -K_2O-S); N (60% urea), S (40% ammonium sulfate) and K (potassium chloride) sources; and two sowing dates, namely: 01/19th/2018, at the beginning of sowing window (DT-1); and 02/27th/2018, seven days after the

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Table 1. Treatments based on N and K application times, at the dose of 400 kg ha^{-1} of 20-00-20, Santa Carmem-MT.

Treat. (DAS)	Incorporated into sowing		1st topdressing		2nd topdressing (35 DAS)	
	%	Stage	%	Stage	%	Stage
Contr.	-	-	-	-	-	-
I/35	50	V0	-	-	50	V8
3/35	-	-	50	VE	50	V8
6/35	-	-	50	V1/2	50	V8
9/35	-	-	50	V2	50	V8
12/35	-	-	50	V3	50	V8
15/35	-	-	50	V4/5	50	V8
18/35	-	-	50	V5	50	V8
21/35	-	-	50	V6	50	V8
0/35	-	-	-	-	100	V8

end of the recommended sowing period (DT-2). Standard fertilization adopted at the farm was based on applying 400 kg ha^{-1} of the formula above. Phosphorus (P) was applied at soybean sowing time, at the dose of 120 kg ha^{-1} P_2O_5, based on using MAP fertilizer (9% N and 50% P_2O_5). The plot comprised eight rows (8 m in length); its four central rows were considered useful areas, and it presented a 1-m border at both ends. The sowing spacing was 0.50 m. Treatments have followed recommendations for maize crops. The Dekalb 290 VTPro3 hybrid was used (3 seeds sown per meter) in the experiment; the final population reached 60 thousand plants ha^{-1}.

Two chlorophyll readings per plant were taken on the "index leaf" (the first leaf below the spike) during flowering, at points located at two-thirds of leaf length, starting from the base, and approximately 2 cm from the leaf margin, on both sides of the vein; five plants per plot were assessed. On the same occasion, ten leaves were collected below and opposite the base of the main spike per plot in order to determine leaf N and K concentrations. Collected leaves were washed in running water and 1% detergent, dried in forced air circulation and renewal oven at 60°-70°C, and ground in a Wiley-type Mill.

Ten (10) maize spikes were randomly removed from each plot at harvest time to assess the number of rows and the number of grains per row and calculate the number of grains per spike. The weight of a thousand grains at 13% moisture content was also assessed. Grain yield was found by harvesting the entire useful plot, which comprised four rows (6 meters long each). Spikes were threshed and weighed, and the standard moisture content was corrected (130 g kg^{-1}). Plant (straw) dry mass was determined right after spikes were harvested. In order to do so, plants (without spikes) deriving from 10 linear meters were weighed, and samples of three whole plants were dried in a forced air circulation oven at 60°C-70°C and weighed to determine their dry matter. Chemical analyses were carried out based on the methodology described by Malavolta et al. (1997) to determine N and K concentrations in the straw, grains, and leaves. Six simple points per plot (0-20 cm; forming a composite sample per plot) were sampled with the aid of a probe and analyzed according to Embrapa (2009) to determine soil K content after maize harvest.

Grain yield data and N and K amounts extracted by plants (grains + straw), were used to calculate nutrient-use efficiency (NUE and KUE, respectively); data were converted into kg Mg^{-1} of produced grains. In addition, the amount of K deriving from the fertilizer (AKDF) in the entire plant was estimated by subtracting the amount of K absorbed in the control plot on each sowing date from the K absorbed in the fertilization treatments (AKDF = AKtreatment – AKcontrol). The sum of the number of degrees-day (DD) was determined according to Gadioli et al. (2000), based on climatological data collected at weather stations belonging to the National Institute of Meteorology (Inmet), which is located in Sinop municipality, 70 km away from the experimental site.

$$DD_{fl} = \sum_{i-1}^{Nfl}\left[\frac{(T\,max_i + T\,min_i)}{2} - Tb\right] \textbf{(if Tm > Tmax}_i\textbf{ and Tmin}_i\textbf{ > Tb);}$$

$$DD_{fl} = \sum_{i-1}^{Nfl}\left[\frac{(T\,m + T\,min_i)}{2} - Tb\right] \textbf{(if Tmax}_i\textbf{ > Tm and Tmin}_i\textbf{ > Tb).}$$

Wherein $Tmax_i$ and $Tmin_i$ refer to maximum and minimum daily air temperature (°C), respectively, whereas Tb and Tm refer to the lowest (10°C) and highest (30°C) basal temperatures, respectively, defined for maize crop (Gadioli et al., 2000). Collected data were tabulated and subjected to analysis of variance through the F test, at a 5% probability level; mean values recorded for treatments were compared through the Scott-Knott test carried out in Sisvar statistical software, at 5% probability level (FERREIRA, 2011).

Results and Discussion

Maize sown on 01/19th (DT-1) flourished at 53 days after sowing (DAS) and recorded accumulated 809 degrees-day (DD) and 560 mm rainfall, in comparison to maize sown in 02/27th (DT-2), which flourished at 46 DAS and recorded accumulated 695 degrees-days (DD) and 375 mm rainfall (Table 2). The water stress experienced early in the cycle by maize sown on 02/27th (Figure 1) (due to poor rainfall distribution in the first three weeks after sowing, when plants had 4-5 fully developed leaves)

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Table 2. Days elapsed between sowing and flowering (DAS-F) (FL), accumulated degrees-day (ADD), accumulated rainfall (mm) until flowering (AR-FL) and total rainfall (TR) in the maize culture cycle on both sowing dates.

Sowing dates	Flowering		AR-FL	TR
	DAS-F	ADD	----------- mm	----------
01/19th (DT-1)	53	809.25	560.5	926.0
02/27th (DT-2)	46	695.03	375.5	445.5

may have forced them to boost physiological events as a strategy to perpetuate the species. Consequently, this process resulted in lower yield (Table 5) since maize production components are defined at the V4-V6 stage (FANCELLI & DOURADO NETO, 2004). Lower moisture-content soil hindered the nutrient-root contact in the late-sowing experiment despite nutrients' availability. This factor resulted in a lower mean yield (2.0 Mg ha^{-1}) than the first sowing time (Table 5). The water amount required by maize ranges from 350 mm to 500 mm, at least; this value was only reached by maize sown on 01/19th (926 mm accumulated until harvest time). The highest water demands were observed at maize emergence, flourishing, and grain formation stages (critical period comprised 15 days before and after male inflorescence emergence). Water shortage affects protein and RNA synthesis, reduces vegetative vigor and pollen yield and fertility, and changes synchrony between male and female inflorescences (FANCELLI & DOURADO NETO, 2004).

Significant interaction between sowing dates and topdressing fertilization times was observed for leaf N (LN), leaf K (LK), K content in plant dry mass (K-PDM), and K content in grains (K-Gr), as shown in Tables 3 and 4. Sowing dates have influenced the total chlorophyll index, N content in plant dry mass (N-PDM), and soil K content (Ksoil) - the highest values were recorded for DT-1 (Table 3). Nitrogen in grains (N-Gr) was significantly higher in plants sown at DT-2 (14.32 g kg^{-1}). It may have happened due to the concentration effect since DT-1 produced 24.2% more grains and plant dry matter (PDM) 2.93 Mg ha^{-1} higher than those observed for DT-2 (Table 5).

The topdressing fertilizer-application affected the N content in grains and soil K content (Table 3). N content in grains was lower in the control treatment (11.77 kg Mg^{-1}) and higher after fertilization. The initial fertilizer application times (from I/35 to 12/35) increased residual soil K

Table 3. Influence of sowing dates and fertilization application times on total leaf chlorophyll index (Chlo-T), leaf N concentration (LN), N in plant dry mass (N-PDM), N in grain (N -GR), leaf K (LK), K in plant dry mass (K-PDM), K in grain (k-Gr) and soil K (K-soil) in maize crop.

(Time - T)	Chlo-T	LN	N-PDM	N-Gr	LK	K-PDM	K-Gr	K-Soil
	SPAD	g kg^{-1}	---------- kg Mg^{-1} -----		g kg^{-1}	------ kg Mg^{-1} ------		mg dm^{-3}
Contr.	52.43	25.95	6.30	11.77 c	23.55	14.90	5.00	51.00 b
I/35	53.93	27.45	6.57	13.91 a	24.05	15.20	4.90	65.00 a
3/35	53.18	28.56	5.06	13.47 b	25.95	15.60	4.50	60.00 a
6/35	54.85	27.34	5.77	14.05 a	27.15	17.10	4.60	60.00 a
9/35	54.38	27.77	7.02	14.24 a	26.65	17.60	4.80	68.00 a
12/35	53.15	27.67	6.52	14.00 a	25.95	17.50	4.70	69.00 a
15/35	55.16	26.41	6.09	14.39 a	27.15	17.90	4.80	57.00 b
18/35	55.61	26.97	6.91	14.30 a	25.95	17.90	4.40	55.00 b
21/35	56.39	25.36	6.45	14.56 a	26.05	17.50	4.20	45.00 b
0/35	58.16	29.98	7.05	13.53 b	25.05	16.20	4.40	55.00 b
(SD)								
1-01/19th	57.08 a	27.66	7.42 a	13.33 b	24.02	11.64	4.94	65.20 a
2-02/27th	52.37 b	27.03	5.33 b	14.32 a	26.92	21.84	4.32	50.80 b
				F test				
T	0.28^{ns}	4.96**	1.31^{ns}	20.09**	3.95**	2.78**	2.89**	2.74**
DT	5.35*	2.89^{ns}	37.68**	76.10**	67.32**	539.71**	43.11**	22.47**
T x DT	0.31^{ns}	3.70**	0.59^{ns}	1.26^{ns}	3.02**	4.41**	2.93**	0.49^{ns}
CV (%)	18.60	6.83	26.70	4.09	6.94	13.11	10.20	26.19

Means followed by different letters in the columns significantly differed from each other in the Scott-Knott test (P<0.05). **; * and ns: significant (P<0.01); (P<0.05) and non-significant, respectively.

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Table 4. Effects of interaction between sowing dates (January 19th: DT-1 and February 27th: DT-2) and fertilization times on leaf N content (LN), leaf K content (LK), K content in plant dry mass (K-PDM) and K content in grains (K-Gr) in maize crop.

	LN		LK		K-PDM		K-Gr	
(T)	**DT-1**	**DT-2**	**DT-1**	**DT-2**	**DT-1**	**DT-2**	**DT-1**	**DT-2**
	------------------ g kg^{-1} ------------------				---------------- kg Mg^{-1} --------------			
Cont.	24.5 bB	27.4 bA	20.9 bB	26.2 bA	12.8 aB	17.0 bA	5.0 aA	5.0 aA
I/35	28.3 aA	26.6 bA	24.3 aA	23.8 bA	10.4 aB	20.0 bA	5.0 aA	4.8 aA
3/35	28.5 aA	28.6 aA	25.1 aA	26.8 aA	11.8 aB	19.4 bA	4.6 aA	4.4 aA
6/35	27.6 aA	27.1 bA	26.3 aB	28.0 aA	12.2 aB	22.0 aA	4.8 aA	4.4 aA
9/35	27.3 aA	28.2 aA	24.3 aB	29.0 aA	11.0 aB	24.2 aA	5.2 aA	4.4 aB
12/35	28.1 aA	27.3 bA	23.3 bB	27.2 aA	11.2 aB	23.8 aA	5.2 aA	4.2 aB
15/35	27.1 aA	25.7 bA	22.7bB	27.4 aA	11.8 aB	24.0 aA	5.0 aA	4.6 aA
18/35	27.0 aA	26.9 bA	23.9 aB	28.0 aA	11.6 aB	24.2 aA	5.0 aA	3.8 bB
21/35	28.3 aA	22.4 cB	24.7 aB	27.4 aA	11.4 aB	23.6 aA	5.0 aA	3.4 bB
0/35	29.9 aA	30.1 aA	24.7 aA	25.4 bA	12.2 aB	20.2 bA	4.6 aA	4.2 aA

Means followed by the same lowercase letters in the column and uppercase letters on the line did not significantly differ from each other in the Scott-Knott test, at 5% significance level.

contents at the end of the cycle. The soil where maize was sown in January recorded 65.2 mg K dm^{-3}, on average. This value was higher than that observed in the area sown in February, which recorded 50.8 mg K dm^{-3} (Table 3). This decrease can be partly explained by higher K absorption by maize plants sown on 02/27th, which recorded K extraction of 151 kg ha^{-1} compared to 146 kg ha^{-1} observed for plants sown on 01/19th (Table 6). Rainfall condition was another factor assumingly causing the K content decrease in the soil for maize sown in February. The rainfall accumulated between 01/19th and 02/27th (40 DAS), which was the interval between the 1st and 2nd sowing date, reached approximately 480 mm; it comprised lower intensity and better distributed daily rainfall events (3 rainfall events of 47 mm day^{-1} and one rainfall event of 62 mm day^{-1}). On the other hand, rainfall accumulated between 02/27th and 04/11th reached approximately 375 mm; however, it comprised larger rainfall volumes (60, 45, 68, and 88 mm day^{-1}), which may have led to increased leaching of the fertilizer applied in the second sowing date. This same region was investigated by de Cavalli et al. (2019b), who applied different K doses to soybean and maize crops and observed substantial nutrient leaching under conditions similar to those in the current study, in soil presenting 550 g kg^{-1} clay, which showed vertical K movement below the 0.5 m layer.

Temperature-related stress conditions may have stimulated plants sown in 02/27th to absorb more K, proportionally to those sown in January, since this nutrient acts as a cell turgidity regulator and controls water loss by stomata. Thus, plants may have increased their transpiration rate and, consequently, absorbed more K via mass flow due to stress (FORNASIERI FILHO, 2007, VAN RAIJ, 2011), as evidenced by the higher LK and K-PDM values recorded for plants sown in DT-2 (Table 4). However, these factors did not influence K content in grains (K-Gr). According to Marschner (1995), a suitable K supply makes it relatively easy to increase its plant content, except for grains, such as cereals, which maintain relatively constant contents.

All treatments recorded different LN contents (Table 4) from that observed for the control based on results of the interaction between sowing dates and topdressing fertilizer-application times in plants sown in 01/19th. Concerning plants sown in 02/27th, treatments 3/35, 9/35, and 0/35 recorded the highest LN values, which were higher than that observed for the control - the fertilizer application carried out at 21/35 DAS recorded the lowest LN value. Suppose one analyzes each treatment (separately) at the two sowing dates; only the control treatment recorded lower LN concentration in plants sown on 01/19th, whereas plants sown on 02/27th recorded the lowest LN value at 21/35 DAS. The LN values herein were close to those Lange et al.

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Table 5. Influence of sowing dates and fertilizer application times on the number of rows per spike (NRS), number of grains per row (NGR), number of grains per spike (NGS), thousand-grain weight (TGW), plant dry mass (PDM) and grain yield (GY).

(T)	NRS	NGR	NGS	TGW	PDM	GY
	----------------- n. -----------------			--- g ---	------- Mg ha^{-1} --------	
Cont.	16.13 b	24.42 b	394.20 c	334.5	5.10 b	7.27
I/35	16.87 a	28.61 a	482.57 a	353.7	6.97 a	9.10
3/35	16.67 a	28.36 a	472.23 b	357.5	6.70 a	10.00
6/35	16.56 a	29.19 a	483.56 a	356.8	6.59 a	9.46
9/35	16.94 a	30.48 a	512.90 a	353.8	7.30 a	9.87
12/35	16.61 a	29.95 a	497.23 a	355.1	6.99 a	10.16
15/35	16.90 a	29.23 a	494.04 a	345.0	7.05 a	9.86
18/35	17.12 a	28.93 a	494.23 a	353.6	7.32 a	9.62
21/35	16.70 a	29.50 a	492.78 a	353.4	7.11 a	9.81
0/35	16.22 b	27.92 a	452.72 b	352.0	5.88 b	9.35
(DT)						
1-01/19th	16.43 b	29.56 a	486.46 a	387.4 a	8.17 a	10.62
2-02/27th	16.91 a	27.76 b	469.55 b	315.7 b	5.24 b	8.28
			F test			
T	3.81**	7.26**	9.62**	1.86^{ns}	4.49**	15.67**
DT	21.73**	21.13**	6.00**	506.89**	196.11**	311.7**
T x DT	0.86^{ns}	0.95^{ns}	0.98^{ns}	0.70^{ns}	0.92^{ns}	2.62*
CV (%)	3.05	6.82	7.22	4.52	15.61	7.0

Means followed by different letters in the columns significantly differed from each other in the Scott-Knott test (P<0.05). **; * and ns: significant (P<0.01); (P<0.05) and non-significant, respectively.

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(2019), in the same region (26 g kg^{-1}). According to Schoninger et al. (2018), Topdressing N application at late maize growth stages (V10 and V12) results in higher N losses due to ammonia volatilization, whereas N application carried out at early growth stages (V4 or V6) enables higher N recovery rates. Silva et al. (2005a), in their turn, compared N fully applied at sowing time to N fully applied as topdressing fertilization and to N applications split into sowing time and topdressing fertilization. Based on their results, the lowest LN concentrations were observed when N was fully applied at sowing time. A similar experiment was conducted by Silva et al. (2005b), who fully applied N at sowing time (15 DAS and 35 DAS) and observed lower concentrations of this nutrient in plants subjected to late fertilizer application. This finding has evidenced variation in results reported in the literature.

Concerning sowing carried out in 01/19th, LK concentration in treatments applied at 12/35 DAS and 15/35 DAS was similar to that of the control and lower than that of other treatments. On the other hand, LK concentration in maize sown in 02/27th was lower than that of the control, at I/35 DAS and 0/35 DAS. It may have happened due to lower rainfall rates observed at 0/35 DAS. Leaf K contents directly affected lower K extraction by the entire plant and K return in straw in the control treatment and at 0/35 DAS (Table 6). The observed absolute values were lower than those observed in a study conducted with different K doses in the same region, which were close to 34-35 g kg^{-1} (LANGE et al., 2019). Results observed under the herein-assessed conditions have evidenced that 50% of fertilizer must be applied in VE-V6, and the remaining 50% must be applied in V8 to reach the highest LK concentrations. Overall, sowing carried out on 02/27 resulted in higher LK contents; this finding corroborated the highest K accumulation in residual maize straw, which was consistently higher at the second sowing date (Table 4). Higher K absorption was observed because this nutrient was absorbed in the soil solution by mass flow; as previously mentioned, it changed stomata perspiration and functioning processes. In addition, given the low rainfall rates recorded at the end of the cycle, although plants had allocated P to leaves and stalks (Tables 3 and 4), they failed to redistribute it to the grains; consequently, K remained in the root dry mass (RDM). Lange et al. (2019) conducted experiments in the same region. They observed that maize sown in soil presenting adequate K contents and subjected to increasing KCl doses recorded increased leaf K concentration, extraction, and export rates under water stress conditions; however, the same response was not observed in a year of well-distributed rainfall events. According to Martineau et al. (2017), K-based fertilization helps maize plants mitigate water stress effects due to lower leaf

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Table 6. Influence of sowing dates and fertilizer application times on N extraction (Ext-N), N export (Exp-N), N return in straw (Ret-N), K extraction (Ext-K), K export (Exp-K) and K return in straw (Ret-K) in maize crops.

(T)	Ext-N	Exp-N	Ret-N	Ext-K	Exp-K	Ret-K
	kg ha^{-1}					
Cont.	116.71	83.74	32.96	108.70 c	35.56	73.12 b
I/35	186.51	138.86	47.64	149.62 a	49.11	100.52 a
3/35	162.41	126.90	35.53	141.96 a	42.64	99.33 a
6/35	179.81	140.77	39.03	153.54 a	46.57	106.96 a
9/35	199.54	146.64	52.89	167.80 a	49.90	117.87 a
12/35	184.74	137.39	47.34	157.80 a	47.12	110.69 a
15/35	183.34	138.04	45.28	163.11 a	46.46	116.65 a
18/35	192.98	140.00	52.99	164.16 a	43.98	120.16 a
21/35	183.43	136.01	47.42	152.33 a	40.56	111.78 a
0/35	166.12	122.72	43.40	130.11 b	40.29	89.81 b
(DT)						
1-01/19th	202.88	141.94	60.94 a	146.48	52.34	94.14 b
2-02/27th	148.24	120.70	27.95 b	151.34	36.09	115.24 a
			F test			
T	15.27**	20.31**	1.97^{ns}	8.05**	6.59**	5.73**
DT	207.28**	73.53**	116.60**	1.46	215.62**	30.05**
T x DT	2.93**	2.03**	1.10^{ns}	1.16	4.84**	1.71^{ns}
CV (%)	10.81	9.64	34.36	13.49	12.51	18.38

Means followed by different letters in the columns significantly differed from each other in the Scott-Knott test (P<0.05). **; * and ns: significant (P<0.01); (P<0.05) and non-significant, respectively.

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evapotranspiration. The authors also observed that stomata remained closed during water stress due to fertilization with K.

The K content found in the grains of plants sown on 01/19th did not differ between fertilizer application times, either because the rainfall was well distributed or because it did not cause water stress (Figure 1). However, applying the 2nd part of the fertilizer at 18 DAS and 21 DAS resulted in lower K contents in the grains of plants sown at DT-2. If one compares sowing dates, it is possible to see that later fertilizer applications in the second sowing date (9/35, 12/35, 18/35 and 21/35 DAS) resulted in lower K content in grains than that observed in plants sown in January. These findings have evidenced that applying the first part of the fertilizer in the region subjected to late sowing (after February 20th) must be carried out up to 9 DAS, on average, to ensure nutrient-use efficiency and increase crop yield (Table 5).

Based on the analysis applied to yield components and grain yield, there was significant interaction between sowing time and topdressing fertilization with crop yield (Tables 5 and 7). Sowing carried out on 01/19th, which lies within the appropriate (ideal) sowing window set for maize crops in the investigated region, had a positive effect on yield components, such as number of grains per row (NGR), number of grains per spike (NGS) and, most of all, thousand-grain weight (TGW) in comparison to results observed for late sowing carried out in 01/27th. These results determined higher grain yield and plant dry mass (PDM) accumulation (Table 5). Concerning fertilization times, complete fertilizer application in a single procedure at 35 DAS reduced the number of rows per spike (NRS), NGS, and PDM values compared to fertilizer applications carried out at other times. This finding is consistent with observations made by Rosa et al. (2017) in a study conducted with the same fertilizer (20-00-20) in the same region.

TGW was decisive and proportional to the recorded yield since late sowing plants recorded TGW equal to 315.7 g, whereas plants sown on 1/19th recorded TGW equal to 387.4 g (an increase of 23%), which resulted in a yield gain of 28% (2.33 Mg ha^{-1}). Larger grains were directly linked to better k-use efficiency by plants and higher crop yield (LANGE et al., 2019) since K contents in grains were 14% higher in plants sown in 1/19th (4.94-4.32 kg Mg^{-1}). This finding has evidenced the need to carry out fertilization at the proper time and with available water so that the applied nutrients can be absorbed by plants, as well as transported and redistributed, together with photosynthesis products, to the grains to enable good starch yield, higher 1000-grain weight and, consequently, higher yield rates.

Yield results have shown that lack of fertilization in the control treatment (Table 7) decreased mean yield values (7.27 Mg ha^{-1}) in comparison to those observed in the other fertilizer application periods, whereas sowing

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Table 7. Effect of interaction between sowing dates (January 19th: DT-1 and February 27th: DT-2) and fertilization times on N extraction, N and K export in the grain, grain yield and difference in yield (1-2) in maize crop.

T (DAS)	N extraction		N export		K export		Grain yield		
	DT-1	DT-2	DT-1	DT-2	DT-1	DT-2	DT-1	DT-2	1-2
	---------------------------- kg ha^{-1} ----------------------------						------------- Mg ha^{-1} -------------		
Cont.	122.8 cA	110.5 bA	82.8 cA	84.7 bA	36.7 cA	34.4 bA	7.68 bA	6.87 bB	0.81
I/35	215.7 aA	157.3 aB	150.6 aA	127.1 aB	54.8 aA	43.5 aB	10.23 aA	7.97 aB	2.24
3/35	182.4 bA	142.4 aB	136.9 bA	116.9 aB	48.6 bA	36.7 aB	10.95 aA	9.03 aB	1.92
6/35	196.4 bA	163.2 aB	146.0 aA	135.6 aA	52.9 aA	40.3 aB	10.57 aA	8.35 aB	2.22
9/35	229.5 aA	169.6 aB	156.5 aA	136.8 aB	59.1 aA	40.7 aB	11.00 aA	8.73 aB	2.27
12/35	222.4 aA	147.0 aB	155.9 aA	118.8 aB	60.1 aA	34.2 bB	11.34 aA	8.98 aB	2.37
15/35	215.1 aA	151.6 aB	150.6 aA	125.5 aB	54.2 aA	38.7 aB	11.54 aA	8.17 aB	3.37
18/35	233.2 aA	152.8 aB	158.2 aA	121.8 aB	56.3 aA	31.6 bB	10.85 aA	8.40 aB	2.45
21/35	215.8 aA	151.1 aB	148.0 aA	124.0 aB	53.8 aA	27.3 bB	11.26 aA	8.36 aB	2.90
0/35	195.3 bA	136.9 aB	133.9 bA	111.5 aB	47.0 bA	33.6 bB	10.75 aA	7.95 aB	2.80

Means followed by the same lowercase letters in the column and uppercase letters on the line did not significantly differ from each other in the Scott-Knott test, at 5% significance level.

carried out within the proper window (in January) produced 0.81 Mg ha^{-1} more than the one carried out in February, in this treatment, due to weather conditions. This behavior was observed for all treatments. Gains up to 3.37 Mg ha^{-1} (at fertilizer application time 15/35) were observed when maize was sown at the ideal time for the investigated region. The highest yield value reached more than 11.30-11.50 Mg ha^{-1} when applications of the first part of the fertilizer were carried out up to 15 DAS. The climate factor, with rainfall events better distributed within the crop cycle, favored plant nutrition and led to higher yield. Plants sown in 02/27th recorded yield higher than 8.50 Mg ha^{-1} when the first part of the fertilizer was applied between 3 and 12 DAS - K export values were also higher in this context.

Plant dry mass (PLM) did not differ between the treatment based on the application of 100% fertilizer at 35 DAS and the control (Table 5) - the other fertilizer application types reached higher PDM values. Rosa et al. (2017) observed similar results in the same region. Silva et al. (2005a) observed reduced maize yield when N fertilization was fully applied at 35 DAS. Complete fertilizer application at 35 DAS impaired N- and K-use efficiency by plants due to nutritional deficit at the beginning of the cycle. This finding corroborates the study by Roscoe & Miranda (2014), who mentioned K as a starter nutrient in maize, as well as the smaller rainfall amount, mainly for the second sowing date, which can be confirmed by lower N extraction and export, as well as by lower K extraction, export and return in PDM (Tables 6 and 7). Sowing carried out on 01/19th produced a plant dry mass of 2.93 Mg ha^{-1} higher than that observed for plants sown on 02/27th due to better water availability conditions.

Rainfall was the factor mainly influencing the herein observed results. The crop sown in January received 926 mm of rainfall, which was well distributed throughout the cycle and during fertilizer applications (Figure 1). This factor increased the amount of water available to plants and made all fertilizer application installments viable to reach a high yield. On the other hand, plants sown in 02/27th did not receive well-distributed rainfall in almost the entire cycle. Maize sown in January was subjected to 560 mm rainfall until flowering time, whereas maize sown on 02/27th was only subjected to 375 mm rainfall. Rainfall condition remained similar after flourishing since maize sown in January was subjected to 366 mm rainfall, whereas maize sown on 02/27th was only subjected to 70 mm. According to Andrade et al. (2000), water stress or lower accumulated rainfall rates decrease carbon availability and spike dry matter participation in critical stages (flowering/grain filling, R1/R2), which are determining factors for parameters like the number and weight of grains.

Plants affected by water stress reduce

carbon demand; consequently, they present decreased yield. According to Prado (2008), besides activating more than 60 enzymes, K accounts for controlling stomata opening and closing, and it helps control water loss and carbon absorption for photosynthesis purposes. The uneven rainfall distribution often observed until flowering in maize sown in February (Table 2) has increased LK contents, which was 12% higher than that of maize sown in January. However, this nutrient was not redistributed to the grains along with photoassimilates; it was retained in the plant, whereas the produced photoassimilates were poorly redistributed, leading to lower grain filling. From flourishing onwards, when nutrient translocation from leaf to grains takes place, there was significant rainfall reduction for maize sown in 02/ 27th, and it reduced water available to the culture, as well as photoassimilates' assimilation and translocation.

Reduced nutrient redistribution can also be confirmed by observing N levels in grains. Maize sown at DT-2 recorded the highest N-Gr values. However, the yield rate recorded for maize sown on this date was lower than that observed on 01/19th. It happened due to the N dilution effect on grains, i.e., nitrogen absorbed when maize was sown at the proper date was assimilated and allocated to the grain; however, N concentrations were higher in February due to higher yield rate (dilution effect). The dilution above was also evident in N exported by grains; 15% more N were exported by maize sown on 01/19th. Well-distributed rainfall events at the first sowing date enabled plants to redistribute N and K to grains. It results in higher N and K exports to the grains, larger grain mass, increased photoassimilate production, and the highest yield rate (24.15%).

The interaction between sowing dates and topdressing fertilization was observed for N extraction and N and K export (Tables 6 and 7). The N content in the residual straw reached 60.9 kg ha^{-1} in maize sown in January; this content was higher than that observed for maize subjected to late sowing. These kg ha^{-1} values recorded for N were quite close to those observed in the survey applied to 10 second-crop maize locations, which recorded 13.1 kg Mg^{-1} grains (Duarte et al. 2018; Duarte et al. 2022).

Potassium (K) extraction and K content in the plant that returned to the soil were higher in the fertilizer installments-based treatment than in the control. This result is also more pronounced for corn sown on 02/27 than 01/19/2018. In other words, plants sown at DT-2 (02/27th) recorded higher K absorption rates; the lowest soil K contents supported this result. However, this nutrient remained in the straw, which presented 115 kg ha^{-1} K at harvest time. This finding matched the lowest yield and, consequently, the low nutrient use to produce photoassimilates.

If one takes into consideration soil K contents higher than 60 mg dm^{-3} up to fertilization installment at 0/12 DAS, which decreased to less

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than 60 mg dm^{-3} later on, as well as K contents in the plant (K content in PDM, its extraction from, and return to the straw), these values were higher from fertilization installment 9/35 to 12/35. This finding highlights the higher use of this nutrient, likely because plants in the field presented a better-developed root system at this stage, and it reduced leaching-related losses since constant rainfall events took place in the two sowing dates in this context. It is worth emphasizing the critical role of second-crop maize as a K source in this system, mainly regarding soybean sown in September/October in this region. It happens because K-rich straw (over 100 kg ha^{-1} of K) can provide substantial amounts of this nutrient to the legume above, as described in another study conducted in this region (Cavalli et al., 2019a). Therefore, producers must consider the K contents in straw during fertilization planning.

Nitrogen (N) extraction and export presented similar behavior (Table 7). The fertilizer installments-based treatment always recorded higher values for these parameters than the control at the two sowing dates. In addition, maize sown on 01/19th also recorded higher N extraction and export rates in fertilized treatments since regular rainfall events provided better nutrient-absorption efficiency. Overall, grains exported 75% of absorbed N (~ 130 kg ha^{-1}), whereas 4 kg ha^{-1} N in the straw returned to the system (cycling), resulting in a total extraction of approximately 170-180 kg ha^{-1} N. This result was similar to that observed in regional studies (LANGE et al., 2019) and corroborated other studies that have recorded 187 kg ha^{-1} N (Coelho & França, 1995).

Higher K export values were observed for maize sown in 01/19th, except for the control treatment, which presented similar export close to 35 kg ha^{-1} K. All fertilization installments applied to maize sown in January exported more K than the control treatment (36.7 kg ha^{-1}); they reached 60 kg ha^{-1} K due to higher fertilizer-use efficiency and grain yield. Concerning sowing carried out on 02/27th, only fertilization times I/35, 3/35, 6/35, 9/35, and 15/35 recorded K export values higher than the others (values close to 40 kg ha^{-1} K). Only the control treatment did not show the difference in this parameter if one compares sowing dates, and it highlights the importance of supplying K to maize, which has a high potential to respond to this nutrient under proper weather conditions. According to Büll (1993), despite the high K absorption by plants, only 20% of it is exported by grains, on average, to reach a yield equal to 9.06 Mg ha^{-1}. Coelho & França (1995) recorded 20%-30% K exports, close to those found in the present study for maize sown in January and February (36% and 24%, respectively). The values above match those reported by Duarte et al. (2022).

The N-use efficiency (NUE-Ext) calculated based on the amount of N extracted by the entire plant (straw + grains) to produce 1 ton

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of grains was higher in maize sown in January (19.11 kg ton^{-1}) than in maize sown at DT-2. The control treatment recorded the smallest amount of extracted N, 16.45 kg ton-1, due to a lack of fertilization (Table 8).

K-use efficiency (KUE-Ext) presented

Table 8. Influence of sowing dates and fertilizer application times, as well as of their interaction, on the efficient use of N (NUE-Ext) and K (KUE-Ext) extracted by plants for each ton of produced grains (1,000 kg) and on the amount of K deriving from the fertilizer (AKDF) in plants, in maize crops.

					KUE-Ext	
(T)	**NUE-Ext**	**KUE-Ext**	**AKDF**		**DT-1**	**DT-2**
	kg Mg^{-1} of grains		kg	%	kg Mg^{-1} of grains	
Cont.	16.45 b	16.46	--	--	15.34 aA	15.36 bA
I/35	18.58 a	18.58	41.0 a	61.7	12.56 aB	17.95 bA
3/35	17.21 b	17.20	33.3 b	50.2	13.53 aB	16.92 bA
6/35	17.88 b	17.88	44.9 a	67.6	13.49 aB	17.33 bA
9/35	19.27 a	19.26	59.1 a	89.1	13.75 aB	19.28 aA
12/35	18.62 a	18.61	49.1 a	74.0	13.46 aB	19.72 aA
15/35	18.95 a	18.93	54.5 a	82.0	14.28 aB	20.46 aA
18/35	19.49 a	19.49	55.5 a	83.6	14.41 aB	19.97 aA
21/35	19.43 a	19.44	43.7 a	65.8	14.59 aB	18.26 aA
0/35	18.23 a	18.22	21.5 b	32.3	13.53 aA	15.70 bA
(DT)						
1-01/19th	19.11 a	13.89	37.7 b	57.0	--	--
2-02/27th	17.70 b	18.05	51.7 a	78.0	--	--
			F test			
T	3.23**	1.74*	3.51**	--	--	--
DT	16.17**	87.25**	10.96**	--	--	--
T x DT	0.57	1.96**	1.185	--	--	--
CV (%)	9.49	14.06	44.7	--	--	--

Means followed by different letters in the columns significantly differed from each other in the Scott-Knott test (P<0.05). **; * and ns: significant (P<0.01); (P<0.05) and non-significant, respectively.

a significant interaction between sowing dates and fertilization times (Table 8), and it was virtually higher in all treatments applied to maize sown in February. This finding has evidenced a higher K demand by plants grown under this condition to produce 1.0 Mg of grains due to the water shortage the crop was subjected. In addition, higher K absorption was observed due to higher demand for water loss control in stomata opening and closing processes and because K was absorbed by mass flow in the soil solution. Thus, higher perspiration led to higher K inflow in plants, up to a limited extent. Maize sown in February recorded higher K extraction per ton of grain between fertilizer applications carried out between 9 DAS and 21 DAS, as well as absorption of approximately 20 kg ton^{-1} of produced grains. No difference in this parameter was observed for maize sown in January.

The amount of K deriving from the fertilizer (AKDF) that corresponded to the kg or % used by the entire plant (66.4 kg of K_2O) was higher at DT-2, which recorded 51.7 kg ha^{-1} K of the total applied amount, and it corresponded to 78% of K used at this time. On the other hand, only 37.7 kg ha^{-1} K were used by plants sown in January (57%), and it highlighted the highest K intake by plants subjected to late sowing. The smallest AKDF observed among the fertilizer application times was recorded for the application carried out at 3 DAS, and when the entire fertilizer was applied at 35 DAS - 21.5 kg ha^{-1} of the applied K was used because the plant had already demanded much of this nutrient. This factor reduced maize yield, mainly in plants sown in 02/27th, which recorded only 7.95 mg ha^{-1} grains after fertilizer application at 35 DAS.

Conclusions

The yield rate recorded for maize sown in January was higher than that observed for maize sown at the end of the recommended time due to favorable water conditions that resulted in the more significant number of grains per spike and in the highest grain mass, which, in its turn, resulted in final yield gain by 2.33 Mg ha^{-1} for maize sown in January.

Topdressing fertilization management has influenced leaf and grain N and K contents and soil K contents at the end of the cycle. The highest residual K content in the soil was observed when maize was sown in January.

Potassium (K) extraction from the soil to produce 1 ton of grains was higher in sowing in late February since the culture was subjected to high water stress and demanded more K. This crop presented similar total K extractions in both sowing dates but different yield rates.

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