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Are biomass partitioning and nutrient accumulation in industrial tomato influenced by NPK fertilization?

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Abstract

This study aimed to evaluate the uptake, accumulation, and partitioning of nitrogen (N), phosphorus (P), and potassium (K) in the tomato crop fertilized with doses of NPK. The main plots consisted of three doses of N: 90, 135, and 180 kg ha^{-1}, P: 270, 405, and 540 kg ha^{-1}, and K: 225, 337, and 450 kg ha^{-1} (equivalent to 50, 75, and 100 % of the fertilization recommendation for industrial tomato), while the subplots consisted of the evaluation periods: 20, 40, 60, 80, and 100 days after transplanting (DAT). The dry matter and the accumulation of N, P, and K were characterized in the different plant components (leaves, stems, fruits, and total). The order of nutrient uptake for the hybrid BRS Sena was defined as K> N> P. The dose corresponding to 50 % NPK resulted in the maximum accumulation of total dry matter of 400 g per plant at 64 DAT and the total accumulation of 10, 1.14, and 14.51 g per plant of N, P, and K, respectively. The intermediate dose of NPK resulted in the maximum accumulation of total dry matter of 468 g and accumulations of 14, 1.6, and 19 g per plant of N, P, and K. At 100 % of the NPK recommendation, there was 514 g per plant of total dry matter, with maximum accumulations of 15, 1.6, and 18 g per plant of N, P, and K. The maximum accumulation rate of N, P, and K occurs at 60, 64, and 70 DAT for the fertilization recommendations corresponding to 50, 75, and 100 % NPK, respectively.

Keywords: *Lycopersicon esculentum*, growing seasons, macronutrients, nutrient uptake

Introduction

The tomato processing industry in Brazil generates 3.2 billion reais per year, with a production of 1.2 million tons in 2019 (WPTC, 2020). In order to ensure economic return with this crop, some factors directly influence the tomato crop cycle, such as genetics, nutrient uptake efficiency, pest and disease resistance, water availability, and weed management (Suzuki et al., 2015).

The supply of nutrients to plants, especially nitrogen, phosphorus, and potassium, is essential to ensure fruit quality and yield. These factors are not synchronously increased due to the amount of nutrients and the period in which they are provided to the plant. Maximum dry matter accumulation often occurs either before or after the stage of maximum fruit quality (Marschner, 2012). Hernandez et al. (2020) verified that reductions in N application equivalent to 50 and 78 % in the tomato crop did not influence fruit quality, although reinforcing the need for elaborate studies to assess the proper time to perform the management with this nutrient.

It is known that the study of the nutrient uptake process by plants results in data on the proper nutritional management for agricultural crops. The rate of nutrient uptake is a tool used in fertilization calculations, expressing nutrient uptake during plant development as a curve (Moraes et al., 2018). These data are essential to estimate the amount of nutrients to be supplied to the crop via fertilization.

Studies that evaluated the rate of nutrient uptake by tomato in Brazil used old cultivars (Garganti & Blanco, 1963; Fernandes et al., 1975, Haag et al., 1978; Fayad et al., 2002), with lower production, higher planting density, and different nutritional management practices from those currently used in cultivation fields.

In this perspective, it is evident that proper fertilization provides the plant with conditions to express

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its genetic potential. However, there is a need to develop studies with nutrient uptake and accumulation by industrial tomato grown in the semiarid region, especially using high-yield hybrids in high-fertility soils. Therefore, this study aimed to evaluate the uptake and accumulation of nitrogen (N), phosphorus (P), and potassium (K) by the tomato hybrid BRS Sena fertilized with NPK.

Material and Methods

The experiment was conducted in the winter period, under field conditions, in the municipality of Jaíba – MG, with a conventional irrigation system, at the following coordinates: 14° 45' S and 43° 33' W, with an elevation of 452 m. The climate of the region was classified as Aw, with a dry winter and a rainy summer. The soil of the area was classified as a Haplic Cambisol with clayey texture (Embrapa, 2013). The area had been previously cultivated with maize, and the crop residues were kept on the surface and incorporated through conventional soil preparation, with two heavy harrowings followed by a light one.

The experimental design was in randomized blocks, in split plots with four replications. The plots consisted of three doses of N: 90, 135, and 180 kg ha^{-1}, P: 270, 405, and 540 kg ha^{-1}, and K: 225, 337, and 450 kg ha^{-1}, corresponding to 50, 75, and 100 % of the maximum recommendation of NPK fertilization for industrial tomato, respectively. This recommendation followed the indications by Filgueira et al. (1999), with adaptations regarding the splitting of the doses for use in fertigation. The subplots consisted of the sampling times: 20, 40, 60, 80, and 100 days after transplanting (DAT).

In the early stage of the study, soil samples (twenty subsamples for one composite sample) were collected at 0 - 20 cm depth for chemical characterization: organic matter: 3.4 dag kg^{-1}; pH (water): 6.5; P (Mehlich 1): 84.4 mg dm^{-3}; K (Mehlich 1): 151 mg dm^{-3}; Na (Mehlich 1): 0.1 mg dm^{-3}; Ca: 10.1 cmol$_c$dm^{-3}; Mg: 2.1 cmol$_c$ dm^{-3}; Al (KCl): 0.0 cmol$_c$dm^{-3}; H+Al: 2 cmol$_c$dm^{-3}; SB: 12.6 cmol$_c$dm^{-3}; t: 12.6 cmol$_c$dm^{-3}; base saturation (V%): 86%; B: 1.9 mg dm^{-3}; Cu: 1.8 mg dm^{-3}; Fe: 6.6 mg dm^{-3}; Mn: 254 mg dm^{-3}; Zn: 8.9 mg dm^{-3}; Prem: 27 mg L^{-1}; EC: 0.3 dS m^{-1}; sand: 16 dag kg^{-1}; silt: 47 dag kg^{-1}; and clay: 38 dag kg^{-1}.

The tomato hybrid used was the BRS Sena, the first national hybrid for this purpose, with excellent mechanical harvesting performance. This hybrid is indicated for planting from February to mid-April, with harvest occurring in up to 110 days (Quezado-Duval et al., 2014).

The treatments with NPK fertilization were managed as follows: at planting (basal fertilization), 20, 100, and 40 % of N, P, and K, respectively, were applied through the 2-30-10 NPK ratio. Both N and K were applied as topdressing, split into six applications, until the beginning of fruit ripening, via fertigation, at 18, 35, 40, 46, 51, and 59 days after transplanting (DAT), using the following fertilizers were: ammonium sulfate, potassium nitrate, and potassium chloride. The remaining nutrients were provided according to the soil analysis recommendation and the fertilization management carried out by the farm.

Each plot was formed by four planting rows, with the two central rows constituting the useful plot, with 30 m length, 5.2 m width, and a total area of 5,616 m², totaling 240 useful plants per plot. The seedlings were produced in 400-cell polystyrene trays with the Carolina Soli® commercial substrate and grown in a greenhouse. Transplantation was mechanically performed when the seedlings had from three to four permanent leaves, in a simple row system, with a 1.3 m spacing between rows and 0.25 m between plants.

The phytosanitary treatments were performed with the application of herbicides (glyphosate, metribuzin), systemic (actara) and contact insecticides (pyrethroid) applied preventively, and fungicides (chlorothalonil, copper hydroxide, famoxadone, and mancozeb) applied according to the schedule of the farm. Irrigation was performed according to the water requirement of the crop using a center pivot irrigation system. The total irrigation depth applied during the crop cycle was 414 mm.

In order to quantify the accumulation of dry matter and N, P, and K, the plants were sampled at 20-day intervals, from 20 to 100 days after transplanting (DAT). Sampling consisted of the collection of four randomly selected plants within the useful plot, as long as they were visually well-nourished and without signs of pest or disease attack. After collected, the plants were properly identified, stored in plastic bags, and subjected to the necessary analyses. After the previous cleaning to remove soil residues, the plants were fragmented into leaves, stems, and fruits, with subsequent drying in a forced-air oven at 65°C until constant weight, thus determining the dry matter weight (biomass) of each component.

Afterward, the samples were ground in a Willey mill with a 2 mm mesh sieve, homogenized, and divided into samples to determine the contents of N, P, and K. N was determined according to the Kjeldahl method (Bremner, 1965). P and K were determined by nitric-perchloric digestion (Tedesco et al., 1995).

The accumulation of N, P, and K (g per plant) in the leaves, stems, fruits, and the total accumulation were also assessed. The accumulation of each nutrient for the respective plant components was quantified using the mathematic expression described below:

Accumulation: MS x T/100

Where:

Accumulation: nutrient accumulation in the plant compartment (g per plant);

MS: dry matter in the plant compartment (kg);

T: nutrient content in the plant compartment (%).

The data were subjected to analysis of variance. Subsequently, when significant for the sources of variation ($p \leq 0.05$), the adjustment of the regression models was performed, which were chosen based on the significance of the regression coefficients and the potential to explain the biological phenomenon in question. The statistical analysis was performed with the statistical software Sisvar 5.3 (Ferreira, 2011).

Considering the times, in intervals of days, as the reference for plant collection, and since the data are quantitative, with a functional correlation between x (days after transplanting) and y (response variable), the choice of the models occurred according to the adjustment (percentage of variance explained, R^2) and better representation of the phenomenon.

The non-linear regression model that was chosen to represent nutrient accumulation in the plant and its different compartments was the three-parameter Gaussian model, as observed in the equation below:

$$\hat{y} = ae[0{,}5(\frac{x-x0}{b})^2]$$

Where:

a = corresponds to the maximum accumulation value;

X_0 = corresponds to the value of x, in DAT, in order to achieve maximum nutrient accumulation;

b = corresponds to the amplitude of the value of x, in DAT, between the inflection point and the maximum point.

Therefore, based on the adjusted model, it was possible to determine, with exactitude, the value of the inflection point (PI) in the curve, as follows:

$$PI = X0 - b$$

The inflection point corresponds to the value of x in which the slope of the adjusted model changes sign; in practice, this corresponds to the value of x, in DAT, in which the daily accumulation rate, even if positive, begins to decrease.

Results and Discussion

The sampling times and doses of NPK fertilization revealed differences ($p<0.05$) for the accumulation of dry matter and N, P, and K in the leaves, stems, and fruits of tomato. The dose corresponding to 50 % NPK fertilization provided a maximum dry matter accumulation of 400.55 g per plant at 85 DAT (Figure 1A. Table 1). At the dose of 75 % NPK, this maximum corresponded to 468.05 g per plant at 93 DAT (Figure 1B. Table 1). For the total dose (100 %) of NPK, the maximum dry matter accumulation was 514.67 g per plant at 90 DAT. The fruit ripening period corresponded to the maximum accumulations of dry matter. The higher nutrient availability in the soil solution increased macronutrient uptake, resulting in higher dry matter accumulation. However, Marschner (2012) explains that the amount of nutrients supplied to the crop influences the quality of plant products as well as the agricultural yield, varying according to the manner and stage of plant development in which the fertilizer is provided.

The dose referring to half of the NPK recommendation (50%) resulted in dry matter accumulation in the stems until 128 DAT, when it reached the maximum accumulation of 119.60 g per plant (Figure 1A. Table 1). As for the total NPK dose, the maximum accumulation occurred at 88 DAT, with 87 g per plant (Figure 1C. Table 1), probably because the high NPK amounts were sufficient to provide higher accumulation during the vegetative stage. The outstanding performance of this hybrid can be attributed to nutrient availability, resulting in better growth performance and higher nutrient accumulation (Isah et al., 2014).

At the dose corresponding to 75% of the NPK recommendation, the maximum dry matter accumulation in the fruits was 342.22 g per plant at 116 DAT (Figure 1B. Table 1). The slow initial tomato growth, until 40 DAT, is related to the process of development of the organs responsible for metabolite acquisition and production, namely roots and leaves, which, at this stage, retain a significant translocation of photoassimilates and metabolites used in their formation (Sari et al., 2019). Subsequently, a higher growth rate was verified until reaching the definitive size, close to 80 DAT, when the fruits became the main drains, after which the tomato plant enters the fruit ripening and senescence stages. Marschner (2012) reports that there is an overlap of the reproductive stage over the vegetative stage, explaining why carbohydrates and photoassimilates are translocated in this manner.

Table 1. Estimates of the adjusted model parameters for the accumulation of dry matter, nitrogen, phosphorus, and potassium as a function of the sampling time, and, for each recommendation of NPK fertilization, the respective values of the inflection points (PI).

	Estimates of the adjusted model parameters														
Organ	A			X_0			B			PI			R^2		
	50%	75%	100%	50%	75%	100%	50%	75%	100%	50%	75%	100%	50%	75%	100%
	---(g per plant)---			----------------------(days after emergence)---------------------										-	
	-----Dry Matter-----														
Leaf	157.7**	164.3**	248.7**	79.23**	80.6**	110.3**	20.2**	20.6**	24.3**	59.0	60.0	86.0	0.99	0.99	0.98
Stem	119.6	63.7**	87.7**	128.0	86.2**	88.6**	41.0	22.3**	18.6**	87.0	63.9	70.0	0.98	0.99	0.99
Fruit	182.3**	342.2**	232.3**	87.4**	116.4*	82.9**	17.9**	31.5	14.3**	69.5	84.8	68.6	0.99	0.99	0.99
Total	400.5**	468.0**	514.7**	85.5**	93.9**	90.4**	21.8**	25.8**	18.2**	63.7	68.1	71.9	0.99	0.99	0.99
	-----Nitrogen-----														
Leaf	3.7**	4.2**	6.4**	74.5**	76.6**	81.9**	21.9*	21.7**	14.4**	52.5	54.9	67.5	0.97	0.99	0.97
Stem	2.0	1.1*	1.6**	128.4	87.3**	85.3**	42.9*	27.1*	18.1*	85.4	60.2	67.2	0.97	0.99	0.98
Fruit	6.1**	11.8*	8.9**	87.3*	112.1*	101.2**	18.4*	30.5	20.2**	68.9	81.6	80.9	0.99	0.98	0.99
Total	10.4**	14.3**	15.2**	85.1*	95.9**	89.9**	22.9*	28.2**	17.9**	62.1	67.6	71.9	0.99	0.99	0.99
	-----Phosphorus-----														
Leaf	0.3**	0.4**	0.5**	76.6**	76.6**	81.5**	22.2**	21.9**	15.6*	54.4	55.0	65.9	0.99	0.99	0.97
Stem	0.2*	1.1**	0.2**	104.1*	79.6**	84.9*	37.1*	25.0**	18.1*	66.9	54.5	66.9	0.94	0.99	0.96
Fruit	0.7**	11.8	1.0**	87.8**	103.4**	106.2**	19.0**	29.8	23.6**	68.7	73.6	82.6	0.99	0.97	0.99
Total	1.1**	14.3**	1.6**	85.8**	91.3**	91.6**	22.8**	27.3**	20.2**	62.9	64.0	71.4	0.99	0.97	0.99
	-----Potassium-----														
Leaf	4.2**	4.6**	6.4**	77.1**	78.2**	82.1**	20.3**	20.0**	14.2**	56.8	58.2	67.9	0.99	0.99	0.98
Stem	4.4	2.3**	2.9*	136.2	83.5**	88.3**	47.1	23.3**	21.8*	89.0	60.1	66.5	0.96	0.99	0.97
Fruit	8.8**	13.6**	9.4**	86.7**	102.5**	97.9**	17.2**	26.2*	20.8**	69.4	76.3	77.1	0.99	0.99	0.99
Total	14.5**	18.7**	17.8**	86.0**	92.4**	89.1**	21.5**	24.8**	18.3**	64.5	67.6	70.8	0.99	0.99	0.99

a: corresponds to the maximum accumulation value; X_0: corresponds to the value of x, in DAT, that provides the maximum accumulation; b: corresponds to the amplitude in the value of x, in DAT, between the inflection point and the maximum point. *,**: significant at 5 and 1 % by the t-test.

The inflection point for dry matter production in the leaves, stems, fruits, and total, at the dose corresponding to 50% of the NPK recommendation, occurred at 59, 87, 69, and 63 DAT, respectively (Table 1). For the intermediate dose (75%), this inflection point occurred at 60, 64, 84, and 68 DAT (Table 1). For the dose corresponding to the total NPK recommendation, a later inflection point was verified at 86, 70, 69, and 72 DAT for the leaves, stems, fruits, and total components. These periods indicate that there was a high demand for water and nutrients, and, after this period, the addition of fertilizers would no longer be efficient as the daily dry matter accumulation rate, even if positive, begins to decrease until the moment of fruit harvest. It is then inferred that the hybrid requires nutrients at a later date, after flowering and at the beginning of fructification.

N was the second most absorbed nutrient by the tomato hybrid BRS Sena, with a maximum accumulation of 10, 14, and 15 g per plant at the doses of 50, 75, and 100% NPK, respectively, from 85 to 95 DAT (Figure 1D, E, and F. Table 1). Lucena et al. (2013) observed maximum accumulation at 93 DAT for the determinate growth hybrid 'SM-16', suggesting that N accumulation increases with the fruit development period.

The fruits allocated greater amounts of N at all NPK doses, followed by the leaves and stems, with accumulations corresponding to 6, 12, and 9 g per plant from 87 to 100 DAT, at the doses of 50, 75, and 100 % NPK, respectively (Figure 1D, E, and F. Table 1). The fruits probably accumulated N until harvest, which was also observed by other authors that studied the tomato crop, such as Prado et al. (2011) with the cultivar Raisa, Fayad et al. (2002) with the hybrid EF-50, and Haag et al. (1978) with an industrial tomato cultivar.

With the progression of crop development (60 DAT), it is possible to observe a redistribution of photoassimilates for fruit formation (Figure 1D, E, and F), reinforcing the role of fruits as the main drains of the hybrid BRS Sena, which was also reported by Moraes et al. (2018), Purquerio et al. (2016), Lucena et al. (2013), Lopes et al. (2011), Fayad et al. (2002), and Grangeiro et al. (2005). This occurs due to the metabolic increase in these organs, which is also associated with the ongoing hormonal activity and cell division (Taiz et al., 2017).

The maximum daily accumulation rate (PI) of N in the leaves occurred at 53, 55, and 68 DAT for the managements with 50, 75, and 100% of fertilization, respectively (Table 1). In the fruits, the maximum point occurred from 69 to 82 DAT (Table 1), corresponding to the period of higher N demand, being then indispensable that the soil application of this nutrient occurs before this period. These results indicate that the highest doses of the NPK recommendation resulted in the increase of the PI, suggesting higher N availability in the soil, prolonging the vegetative period of the tomato crop, and resulting in higher accumulations of this nutrient in the fruits.

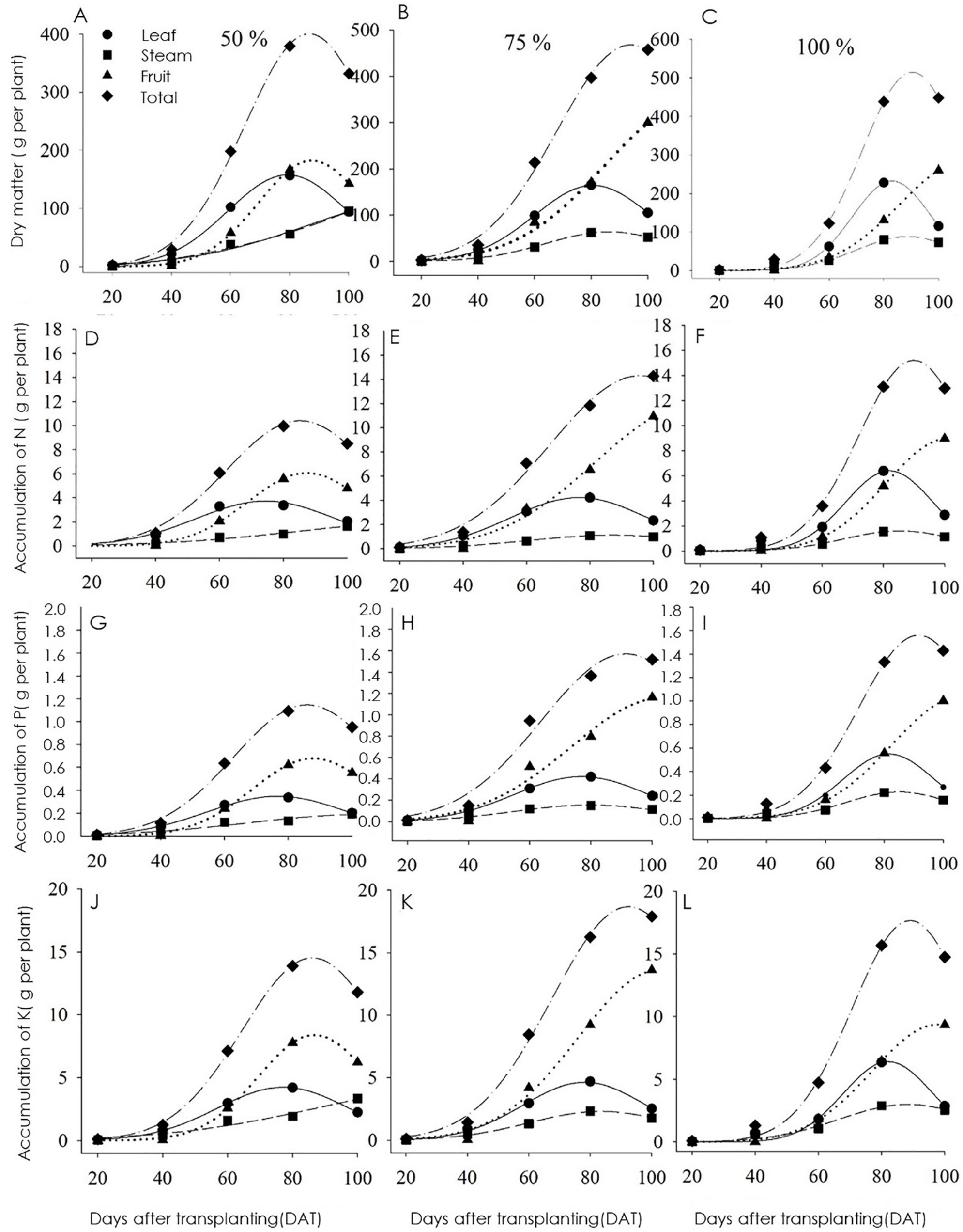

Figure 1. Sampling time (DAT) and recommendation of NPK fertilization corresponding to 50 %, 75 %, and 100 % on total dry matter accumulation (A, B, and C) in the leaves, stems, and fruits, and nitrogen (D, E, and F), phosphorus (G, H, and I), and potassium (J, K, and L) accumulation in the tomato hybrid BRS Sena.

Among plant components, the leaves were responsible for the relative accumulation of approximately 70 and 51 % of the N in the shoot of tomato plants, at 40 DAT, at the doses corresponding to 50 and 75 % NPK (Figure 2A and B). The total NPK recommendation resulted in a relatively high N accumulation (47 %) in the stems, initially at 20 DAT, then increasing (54 %) to a higher accumulation in the leaves, at 60 DAT (Figure 2C). After 60 DAT, a period that coincides with the beginning of the reproductive stage, there is a decrease in N accumulation in the shoot, with the fruits being responsible for the highest relative accumulation, except for the total dose (100 %), which, until 80 DAT, resulted in higher accumulations for the leaf component. This dose probably corresponded to the extension of the vegetative period in the tomato crop. Bastos et al. (2013) report that the tomato crop requires N during its vegetative development since this nutrient is mainly used in the formation of the photosynthetic canopy.

P was the macronutrient with lower accumulation, corresponding to 1.1, 1.6, and 1.6 g per plant from 85 to 91 DAT at the NPK recommendations of 50, 75, and 100 %, respectively (Table 1). Moraes et al. (2018), Purquerio et al. (2016), Lucena et al. (2013), Prado et al. (2011), and Fayad et al. (2002) also observed that P was the least accumulated macronutrient throughout the development of the tomato crop. Marschner (2012) reported that the amount of P required by the plants during their vegetative growth is relatively low, with mean values from 3 to 5 mg g^{-1} in the leaves.

The stems were the compartments that accumulated less P throughout the crop cycle, with 0.19, 0.15, and 0.23 g per plant from 79 to 100 DAT, respectively, at 50, 75, and 100 % of the NPK recommendations (Table 1). The fruits accumulated higher amounts of this nutrient, with 0.68, 1.15, and 1.04 g per plant from 87 to 100 DAT, respectively, at the doses corresponding to 50, 75, and 100 % NPK. It is verified that the period of higher accumulation also coincides with the fruit development period. P shows greater redistribution in reserve organs and produces fatty acids during fruit development and ripening (Marschner, 2012).

The supply of P is important during the entire cycle of the hybrid, evidencing the need for the management of this macronutrient so that it may be available in the soil solution during the crop cycle. The study by Zhu et al. (2018) clarifies that P availability to the tomato crop during development is even more important than the use of higher doses at planting. However, this factor is aggravated in Brazilian soils, which show high specific phosphorus adsorption, modified by the soil clay fractions (Vilar et al., 2010; Novais & Smyth, 1999).

The inflection point (Table 1), corresponding to the period in which, even with a positive P uptake, the maximum accumulation rate begins to decrease, occurred from 54 to 82 DAT for the fertilization recommendations of 50, 75, and 100 % NPK. Therefore, P should be readily available in the soil solution before this period in order to be absorbed.

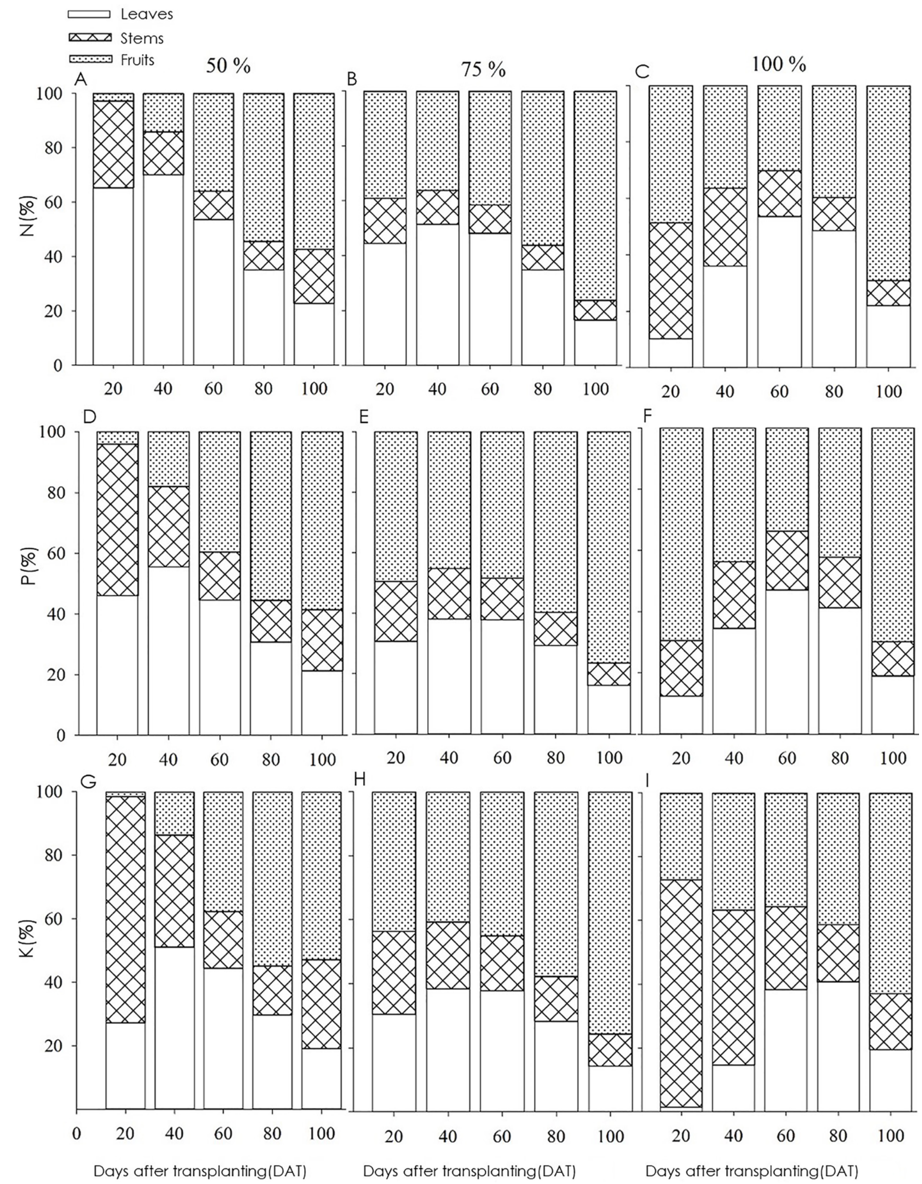

Figure 2. Sampling time (DAT) and recommendation of NPK fertilization corresponding to 50 %, 75 %, and 100 % on the relative accumulation of nitrogen (A, B, and C), phosphorus (D, E, and F), and potassium (G, H, and I) in the leaves, stems, fruits of the tomato hybrid BRS Sena

Higher relative accumulations of P in the vegetative biomass were verified until 60 DAT, with 45 % for half of the NPK recommendation (Figure 2D), after which the relative accumulation was higher in the fruits (59 %), at 100 DAT. On the other hand, at the intermediate NPK recommendation, the stems showed higher relative accumulation (48 %) until 60 DAT, with later redistribution to the fruits (76 %) until the end of the crop cycle (Figure 2E). At the total NPK dose, there was, initially (20 DAT), a higher P demand for the stems (69 %), and until 80 DAT, the shoot biomass retained the highest relative accumulations (58 %). At the end of the cycle, the fruits showed higher (70 %) relative accumulation (Figure 2F), possibly because, at this dose, there was a luxury uptake of P, which prolonged the vegetative cycle of the plant.

K was the most accumulated macronutrient by the hybrid BRS Sena (Table 1), which was also verified by Moraes et al. (2018), Purquerio et al. (2016), Lucena et al. (2013); Lopes et al. (2011); Prado et al. (2011); Fayad et al. (2002); Haag et al. (1978), and Garganti and Blanco (1963), with maximum accumulations of 14, 19, and 18 g per plant from 86 to 92 DAT (Table 1), corresponding to the fertilization recommendations of 50, 75, and 100 % NPK, respectively. Lucena et al. (2013) verified that K was the most absorbed nutrient by the tomato hybrid SM-16, with a maximum accumulation of 305 kg ha^{-1} at 90 DAT, revealing the importance of this nutrient in the tomato fruiting stage, probably due to its role involving the synthesis and biosynthesis of lycopenes, organic acids, sugars, and vitamin C (Marschner, 2012).

Fratoni et al. (2016), in studies with doses of K in Italian tomato, concluded that this nutrient should be applied at the beginning of flowering, a period that does not coincide with fruiting and the final fruit formation reported in the present study.

The leaves achieved maximum K accumulation from 77 to 82 DAT, with 4, 5, and 6 g per plant at the doses corresponding to 50, 75, and 100 % NPK, respectively (Table 1. Figure 1J, K, and L). The fruits were the organs that most absorbed K at all NPK doses, with maximum values of 8, 14, and 9 g per plant from 86 to 100 DAT. Since K is extremely mobile in the plant and is related to sugar transport to the fruits, the redistribution of this nutrient is noticeable, decreasing the leaf contents with the consequent increase in the fruits, also reinforcing the drainage potential of this organ (Fratoni et al., 2016)

The PI of this nutrient was verified from 64 to 71 DAT (Table 1), from which the accumulation rate begins to decrease. Thus, it is worth noting that K should be available in the soil solution before this time as any applications after the period would have little influence on fruit production and quality. Nowaki et al. (2017) suggest that K should be provided to the plant through split applications as this macronutrient participates in processes that control vegetative growth, flowering, and fruit formation and quality.

Until 60 DAT, at the dose corresponding to 50 % NPK, the highest accumulation percentages were observed in the vegetative organs (62 %), and when close to 100 DAT, nutrients were reallocated to the fruits (55 %) (Figure 2G). For the intermediate dose of NPK, since the initial development of the crop (40 DAT), K was required in large amounts (41 %) for the formation of inflorescences and consequently fruits (Figure 2H). After 60 DAT, a higher K accumulation is verified in the formation of leaves (38 %) and stems (17 %), with later redistribution for fruit ripening (76 %) as the cycle advances. At the total NPK recommendation, shoot biomass showed greater amounts (59 %) of this macronutrient until 80 DAT (Figure 2I), subsequently allocating K for final fruit development (63 %).

In general, the PI for half of the recommendation of NPK fertilization occurred at 60 DAT for the studied macronutrients, reinforcing the need for topdressing fertilization before this period in order for the tomato crop to absorb the nutrients and possibly result in dry matter gain. The intermediate recommendation of NPK fertilization resulted in an inflection point from 64 to 67 DAT for NPK, which indicates that topdressing fertilization should be performed before this period in order for the nutrients to be readily available in the soil solution. For the total recommendation of NPK fertilization, the points of maximum accumulation occurred later, at 72 DAT, inferring that the prolongation of the inflection point can be caused by the greater nutrient availability in the soil at this dose, favoring the prolongation of the vegetative stage in this hybrid.

At the end of the crop cycle, the N percentages of 58, 82, and 59 % were exported at the fertilization recommendations of 50, 75, and 100 % NPK, respectively. Regarding the amount of P, the percentages of 59, 74, and 66 % were extracted at the fertilization recommendations of 50, 75, and 100 % NPK. For the amount of K extracted at harvest, the intermediate dose of the NPK recommendation was responsible for the highest K removal, with a total of 73 %. The fertilization recommendations of 50 and 100 % NPK extracted the respective percentages of 58 and 53 % from the area, reinforcing the need to resupply these macronutrients via fertilization in subsequent cultivation systems.

The amount of macronutrients exported from the cultivation area by the fruits corresponded to 121, 13, and 167 kg ha^{-1} for N, P, and K at the dose corresponding to half of the recommendation of NPK fertilization, resulting in the productivity of 116.62 t ha^{-1} and industrial yield of 17.6 t ha^{-1}. On the other hand, the intermediate dose of NPK fertilization resulted in the productivity of 104.39 t ha^{-1} and industrial yield of 16.7 t ha^{-1}, extracting 235, 23, and 272 kg ha^{-1} of N, P, and K, respectively. The total NPK recommendation resulted in the productivity of 113.23 t ha^{-1} and industrial yield of 18.4 t ha^{-1}, extracting 179, 21, and 188 kg ha^{-1} of N, P, and K, respectively. These results indicate that the use of half of the fertilization recommendation (50 %) of NPK is significant for providing lower nutrient removal and ensuring high yield values. Hernandez et al. (2020) reinforce that the reduction of nitrogen fertilization in the tomato crop does not interfere with its quality and yield.

The remaining nutrients in the area, for all NPK fertilization recommendations, should be considered for the next cultivation cycles as they can be incorporated into the soil in the form of crop residues.

Conclusions

The total dry matter accumulation in the tomato hybrid BRS Sena followed an ascending order of maximum accumulation corresponding to 400, 468, and 514 g per plant from 64 to 72 DAT for the fertilization recommendations of 50, 75, and 100 % NPK, respectively.

The inflection point of N, P, and K occurs at 60, 64, and 70 DAT for the fertilization recommendations corresponding to 50, 75, and 100 % NPK, respectively.

The exportation of macronutrients by fruits in the tomato hybrid BRS Sena for half of the fertilization recommendation corresponded to 121, 13, and 167 kg ha^{-1} for N, P, and K, respectively. For 75% of the recommendation, the extraction corresponded to 235, 23, and 272 kg ha^{-1} of N, P, and K. For 100% of the recommendation, 179, 21, and 188 kg $ha^{-1}$of N, P, and K were exported.

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