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Biomass production and nutrient accumulation in physalis in two edaphoclimatic conditions

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ABSTRACT. In Brazil, although there is a growing demand for physalis in the food industries, information on the nutritional management of the crop is still incipient. This study aimed to evaluate the biomass production and accumulation of nutrients in the shoots and fruit of physalis in two cultivation sites. Two field experiments were conducted, one where the soil was Typic Quartzipsamment in the municipality of Diamantina and the other where the soil was Rhodic Hapludox in the municipality of São João Evangelista, Minas Gerais State, Brazil. The experiments were conducted in a randomized complete block design with four replicates. The treatments were the evaluation period. Samples were collected every 15 days the day of planting of the seedlings in the field for a period of 240 days. Dry matter and nutrient accumulation in shoot and fruit were evaluated. The biomass production and nutrient accumulation were higher in the edaphoclimatic conditions at São João Evangelista compared to the conditions at Diamantina. Macronutrient accumulation was in the following order: N > K > Ca > S > Mg > P in shoot and N > K > P > S > Ca > Mg in fruit. Micronutrient accumulation in shoot and fruit was in the following order: Fe > Mn > Zn > B > Cu.

Keywords: absorption rate; cover fertilization; *Physalis peruviana* L.

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Introduction

The economic feasibility of cultivating small fruit has only recently been recognized in Brazil, and has been attracting the attention of producers, traders, and consumers in the recent years (Silva et al., 2017). Among these small fruit with potential for cultivation and commercialization across several regions of Brazil, physalis (*Physalis peruviana* L.) is considered promising. Physalis behaves either as an annual or a perennial plant depending on the production environment, climate, soil, and agronomic management (Muniz et al., 2014). In the early growth phases, the species presents a herbaceous habit, and from the second year onwards, it forms a shrub that can reach 1.5 to 2.0 m in height. It has great capacity for branching, needing support to keep the branches upright (Fischer & Lüdders, 2002; Lima, Gonçalves, Tomaz, Fachinello, & Rufato, 2010). Fruit are classified as climacteric, found inside a chalice formed by five sepals which is popularly called bollworm, which protects them against insects, birds, pathogens, and adverse weather conditions (Rufato, Muniz, Kretzscmar, Rufato, & Gatiboni, 2012). The fruit are rich in vitamin A and C, as well as Ca, P, Fe, and fibers (Díaz, Pinto-Muñoz, Castro, & Rodríguez, 2011).

Plant growth is the increase in dry mass, volume, length, and area as a result of division, expansion, and differentiation of cells (Fageria & Moreira, 2011). It is considered a fundamental biological process, studied in a wide range of scientific fields, integrating the scales from physiology to community dynamics and ecosystem properties (Taiz & Zeiger, 2017). Nutrient accumulation is the amount of nutrients in the dry mass of each part of the plant (Salazar, Jones, Chaves, & Cooman, 2008; Tripathi et al., 2015).

The development phase of the plant determines the amount of nutrients it absorbs (Moschini et al., 2017; Silva et al., 2017; Silva, Cruz, Braga Neto, Gonçalves, & Silva, 2018). The amount of nutrients accumulated and exported by the various organs of the plant is important for the management of fertilization (Martínez, Sarmiento, Fischer, & Jiménez, 2008; Torres et al., 2015; Parra, Bucheli, Marín, Coral, & Lagos, 2015). Therefore, it is necessary to study the uptake of nutrients as a function of time to predict how, when, and how much fertilizer should be applied. Thus, quantitative and qualitative aspects of fertilization can be observed when evaluating the nutritional requirements of plants (Malavolta, 2006; Marschner, 2012).

Knowledge of the amount of nutrients accumulated in physalis helps in the recommendation of a balanced fertilization, which would provide adequate nutrition and contributes to maximizing the potential of this species.

Thus, the objective of this study was to evaluate the biomass production and accumulation of nutrients in the shoots and fruit of physalis in two cultivation sites.

Material and methods

The experiments were conducted under field conditions at two sites. The first, where the experiment was conducted from March to November 2017, was located at Diamantina (DTA), Minas Gerais State, Brazil (18º 14' S, 43º 36' W, 1,250 m a.s.l.), in Alto do Vale do Jequitinhonha, where the soil classified as Typic Quartzipsamment according to the Soil Taxonomy (Soil Survey Staff, 2010) and as Neossolo Quartzarênico Órtico típico according to the Brazilian classification (Santos et al., 2018). The second site, where the experiment was conducted from February to October 2019, was located at São João Evangelista (SJE), Minas Gerais State, Brazil (18º 33' S, 42º 45' W, 690 m a.s.l.), in the Vale do Rio Doce, where the soil was classified as Rhodic Hapludox according to the Soil Taxonomy (Soil Survey Staff, 2010) and Latossolo Vermelho distrófico according to the Brazilian classification (Santos et al., 2018). Chemical characterization (Silva, 2009) and granulometric analysis (Teixeira, Donagemma, Fontana, & Teixeira, 2017) were undertaken at both the sites, and the results are presented in Table 1.

Based on the soil chemical analysis (Table 1), liming, with limestone (380 g kg^{-1} of CaO, 125 g kg^{-1} of MgO, and 95% PRNT), was carried out using the base saturation method to increase the base saturation to 65% (Rufato et al., 2012).

The production of physalis seedlings was carried out in a greenhouse at the cultivation sites using seeds from the Epamig/Sul experimental unit in Maria da Fé, Minas Gerais State (22º 18' S, 45º 22' W, 1,278 m a.s.l.). The seeds were sown in styrofoam trays with 72 cells each. After germination, seedlings were transferred to plastic bags that were 0.5 dm^3 in volume, containing Bioplant®, a commercial substrate. The seedlings remained in the plastic bags under a screen with 30% shading and intermittent micro-sprinkling until they were ready for transplanting to the field, which occurred at 50 days after sowing at the DTA site and 30 days after sowing at the SJE site.

Table 1. Chemical and textural characterization of soils prior the implementation of experiments.

Characteristic	Unit	Soil	
		TQ	RH
pH_{water}	-	6.7	5.3
P	mg kg^{-1}	3.7	3.2
K	$mmol_c$ kg^{-1}	0.3	0.9
Ca	$mmol_c$ kg^{-1}	7.5	12.9
Mg	$mmol_c$ kg^{-1}	6.0	5.7
Al	$mmol_c$ kg^{-1}	1.0	9.1
T	$mmol_c$ kg^{-1}	32.3	53.9
m	%	7.0	32.0
V	%	43.0	36.0
B	mg kg^{-1}	0.3	0.2
Cu	mg kg^{-1}	1.2	0.8
Fe	mg kg^{-1}	32.0	128.0
Mn	mg kg^{-1}	21.0	68.0
Zn	mg kg^{-1}	0.8	0.5
OC	g kg^{-1}	4.8	9.2
Sand	g kg^{-1}	860	320
Loam	g kg^{-1}	30	130
Clay	g kg^{-1}	110	560

pH_{water}: Soil: water 1:2.5. P, K, Cu, Fe, Mn, and Zn: Mehlich-1 extractor. Ca, Mg and Al: KCl 1 moL L^{-1} extractor. B: Hot water method. T: Cation exchange capacity at pH 7.0. m: Aluminum saturation. V: Bases saturation. OC: Organic carbonic by Walkey-Black method. Sand, silt, and clay: Pipette method. TQ: Typic Quartzipsamment. RQ: Rhodic Hapludox.

Following Rufato et al. (2012), the seedlings with four to five expanded leaves were planted in the field, on May 22, 2017 at DTA and on February 18, 2019 at SJE at a spacing of 3.0 x 1.0 m, spacing, in pits that measured 0.3 x 0.3 x 0.3 m, resulting in a crop a density of 3,333 plants per hectare. The plants were supported using a vertical spreader, which consisted of 2.0 m high eucalyptus posts for staking the plants, with the first wire for staking at 0.4 m above the soil and the second at 1.2 m. The plants were secured with tape when necessary. Plant growth was free, with no formation, fruiting or renewal pruning.

Fertilization was recommended by Rufato et al. (2012) for physalis: planting fertilization was 34 kg ha^{-1} of P (simple superphosphate); cover fertilization was applied at doses of 50 of N (ammonium sulfate) and 83 kg ha^{-1} of K (potassium chloride), divided into four applications, which were applied every 15 days from 15 days after planting (DAP) the seedlings. Fertilization with micronutrients was performed in the first application of N and K cover fertilization with applications of 1 of B (borax) and 2 kg ha^{-1} of Zn (zinc sulfate). Micronutrient fertilization was based on availability in the soil (Table 1) and recommendations for tomato crop (Filgueira, Obeid, Morais, Santos, & Fontes, 1999), a species that requires similar cultural practices as physalis (Muniz et al., 2014). During the experimental period, meteorological data were collected at both cultivation sites to calculate the average temperature and accumulated biweekly rainfall (Figure 1). The data were collected through the Inmet (*Instituto Nacional de Meteorologia*) automatic meteorological station at DTA (18º 13' S, 43º 38' W, 1,359 m a.s.l.) and Guanhães (18º 47' S, 42º 56' W, 853 m a.s.l.), which was located 14 km away from the experimental area at DTA and 37 km at SJE.

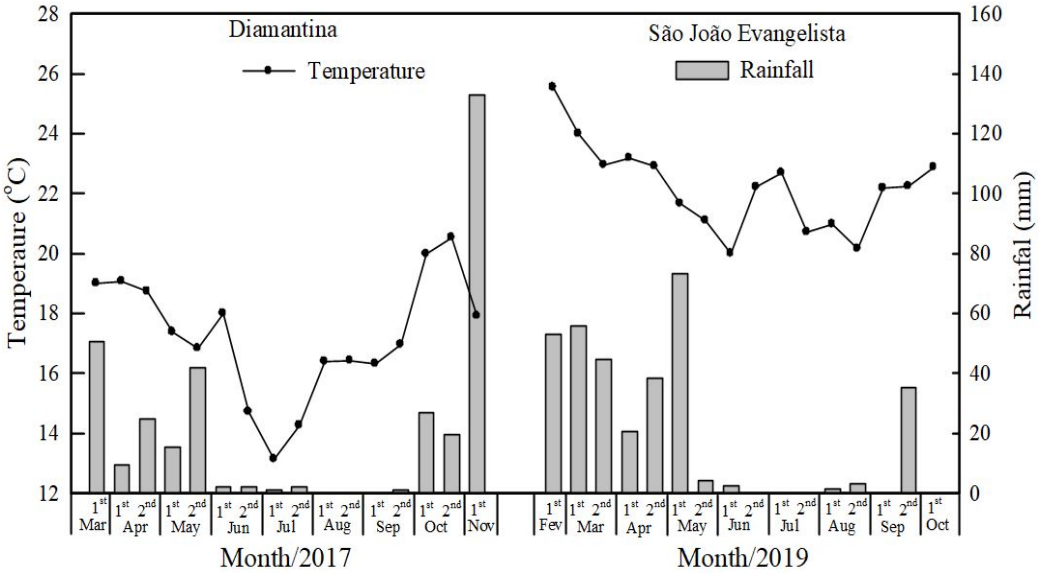

Figure 1. Average temperature and accumulated biweekly rainfall during the experimental period in Diamantina and São João Evangelista, Minas Gerais State, Brazil. Source: *Instituto Nacional de Meteorologia* (Inmet, 2020)

At both cultivation sites, drip irrigation was used. The drip tape was installed at distance of 0.10 m from the planting line, with self-compensating drippers spaced at 0.20 m, with a flow rate of 1.6 L $hour^{-1}$. The management of irrigation was based on the use of the Class A tank, adopting a fixed irrigation shift of one day. The applied irrigation depth was calculated based on the daily evaporation of the Class A tank, using tank (Kp) and crop (Kc) coefficients based on the phases of the tomato crop cycle in a conventional planting system (Santana et al., 2011). The water depth was 4.5 mm per day, which was supplemented when necessary.

The experiments were carried out in a randomized complete block design with four replications, with the sampling period as treatments. The experimental plot consisted of 12 plants with a drawing of the useful plot of two central plants within each block and sampling period. Sampling started at the time of planting the seedlings in the field at each cultivation site, when leaves and stems were collected, which was considered as the first day. From the planting date of the seedlings up to 240 DAP, leaves, stems, and fruit were collected every 15 days.

The collected plant material was first washed in running water, to remove excess soil and then with deionized water. It was then packed in a paper bag and dried in a forced air circulation oven at 65ºC until constant weight was reached. The dried plant material was weighed using an analytical balance and the dry matter (DM) of the shoot (sum of the dry matter of leaves, stems and fruit) and fruit materials were noted. The plant materials were then milled a Wiley-type mill with a fine sieve (40 mesh). Total concentrations of N (sulfuric acid digestion/Kjeldahl method), P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn (nitric-perchloric acid digestion), and B (incinerated in muffle furnace) in plant material were determined (Silva, 2009).

The accumulation of macronutrients and micronutrients per hectare in shoot and fruit were calculated using the following Equation 1 and 2:

$$Macronutrient\ accumulation\ =\ [DM\ (kg\ ha^{-1})\ \times\ macronutrient\ concentration\ (g\ kg^{-1})]/1000 \quad (1)$$

$$Micronutrient\ accumulation\ =\ [DM\ (kg\ ha^{-1})\ \times\ micronutrient\ concentration\ (g\ kg^{-1})]/1000 \quad (2)$$

The accumulation of dry matter and nutrients in shoot and fruit were subjected to analysis of variance (Sisvar® software 5.6) and regression analysis (Microsoft Office Excel 2010 software). The adjustment for the accumulations as a function of time was performed using non-linear sigmoidal regression models with three parameters, as described in Equation 3:

$$\hat{y}\ =\ a\ /\ 1\ +\ exp\ -\ ((x\ -\ x0)\ /\ b) \quad (3)$$

where: $\hat{y}$ is accumulation of dry matter and nutrients; a is the maximum accumulation (MA) value; x_0 is the inflection point; and b is the adjustment parameter.

The inflection points of the adjusted curves corresponded to the moments when the maximum rates of accumulation of dry matter and nutrients in the shoot and fruit occurred. The maximum daily accumulation rate (Mdar) was determined by the accumulation of dry matter and nutrients at the inflection point minus the accumulation on the previous day.

The minimum (CP_{min}) and maximum (CP_{max}) curvature points in the sigmoid models were calculated according to the method mentioned by Venegas, Harris, and Simon (1998), using the following non-linear Equation 4 and 5:

$$CP_{min}\ =\ x_0\ -\ 2b \quad (4)$$

$$CP_{max}\ =\ x_0\ +\ 2b \quad (5)$$

CP_{min} indicates the moment in the accumulation curve when significant gains in the accumulation of dry matter and nutrients begin. Conversely, CP_{max} indicates the moment when the accumulation of dry matter and nutrients begin to stabilize.

Results and discussion

Accumulation of dry matter (DM) and nutrients in the shoot and fruit of the physalis plants differed between the sampling periods and cultivation site ($p < 0.001$). Accumulations increased according to the sigmoidal model as a function of the sampling period (Figure 2 and Table 2).

On the other hand, the accumulation of DM in the fruit of physalis started from 75 DAP (Figure 2a) with the beginning of fruit yield at both sites, increasing from the time corresponding to CP_{min} until reaching MA at the time corresponding to CP_{max} at 162 DAP at DTA and 154 DAP at SJE (Table 3).

Similar to the accumulation of DM in the shoots and fruit (Figure 2a), it was observed that up to 60 DAP, the macronutrient (Figure 2b to g) and micronutrient accumulations (Figure 2h to l) were small at both sites. From the time corresponding to CP_{min}, the accumulation of nutrients in the shoots increased sharply, reaching MA of nutrients in the shoots of the plants at the time corresponding to CP_{max} (Table 3). Similar to the accumulation of DM in fruit (Figure 2a), macronutrient (Figure 2b to g), and micronutrient accumulations (Figure 2h to l) started slowly at 75 DAP; starting from the time corresponding to CP_{min}, the accumulations increased until reaching MA at CP_{max} (Table 3).

The physalis shoot showed higher accumulations of DM and nutrients at SJE compared to DTA (Table 3). The highest accumulations observed at SJE were related to the achievement of a higher Mdar at this site (Table 3). The time to achieve Mdar (X_{Mdar}) was shorter at SJE than at DTA (Table 3). In addition, the MA of DM was different between shoot and fruit at both cultivation sites, with higher accumulation in at DTA and in shoot at SJE (Table 3). The largest accumulations are related to the achievement of greater Mdar in parts of the physalis plants (Table 3). The difference in X_{Mdar} for nutrients between shoot and fruit at DTA was shorter when compared with SJE (Table 3). The Mdar of nutrients was similar between the shoot and fruit at DTA, and higher in the shoot at SJE (Table 3).

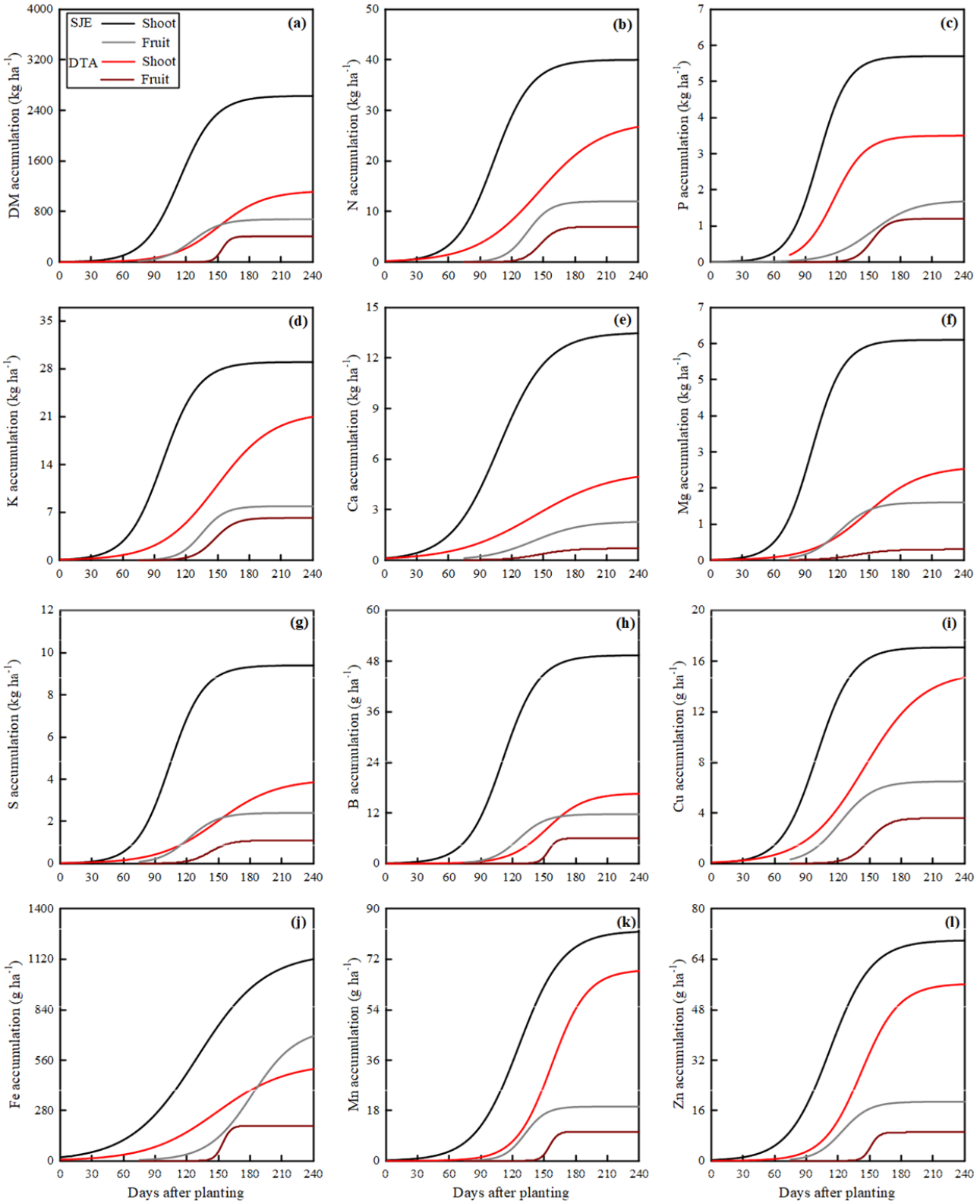

Figure 2. Accumulation of dry matter (DM) and nutrients in the shoot and fruit of physalis as a function of the period elapsed after planting the seedlings in Diamantina (DTA) and São João Evangelista (SJE), Minas Gerais State, Brazil.

Maximum accumulations are related to the highest Mdar of nutrients in the shoot and fruit of the physalis plants at both sites (Table 3). Therefore, the sequence of nutrient accumulation is related to the Mdar values (Table 3), which was the same in shoot of the physalis plants at both cultivation sites. The decreasing order of accumulation of macronutrients in the shoot was N > K > Ca > S > Mg > P, and of micronutrients was Fe > Mn > Zn > B > Cu (Table 3). In fruit, the order of macronutrient accumulation was N > K > P > S > Ca > Mg, and of micronutrients was Fe > Mn > Zn > B > Cu (Table 3).

Table 2. Regression equations for the accumulation of dry matter (DM) and nutrients in the shoot and fruit of physalis as a function of the time elapsed after planting the seedlings in Diamantina and São João Evangelista, Minas Gerais State, Brazil.

Variable	Part	Diamantina		São João Evangelista	
		Model	R^2	Model	R^2
DM	Shoot	$\hat{y}$ = 1031/1 + exp(-(x - 151)/22))	0.96	$\hat{y}$ = 2630/1 + exp(-(x - 114)/17))	0.93
	Fruit	$\hat{y}$ = 407/1 + exp(-(x - 154)/4))	0.94	$\hat{y}$ = 678/1 + exp(-(x - 126)/14))	0.85
N	Shoot	$\hat{y}$ = 27.9/1 + exp(-(x - 146)/30))	0.95	$\hat{y}$ = 40.0/1 + exp(-(x - 103)/18))	0.96
	Fruit	$\hat{y}$ = 7.0/1 + exp(-(x - 147)/8))	0.90	$\hat{y}$ = 12.0/1 + exp(-(x - 135)/11))	0.90
P	Shoot	$\hat{y}$ = 1.7/1 + exp(-(x - 153)/20))	0.95	$\hat{y}$ = 5.7/1 + exp(-(x - 102)/14))	0.90
	Fruit	$\hat{y}$ = 1.2/1 + exp(-(x - 153)/8))	0.92	$\hat{y}$ = 3.5/1 + exp(-(x - 117)/15))	0.90
K	Shoot	$\hat{y}$ = 21.7/1 + exp(-(x - 149)/27))	0.95	$\hat{y}$ = 29.0/1 + exp(-(x - 98)/17))	0.96
	Fruit	$\hat{y}$ = 6.2/1 + exp(-(x - 147)/10))	0.90	$\hat{y}$ = 7.9/1 + exp(-(x - 135)/11))	0.90
Ca	Shoot	$\hat{y}$ = 5.3/1 + exp(-(x - 142)/37))	0.95	$\hat{y}$ = 13.5/1 + exp(-(x - 108)/23))	0.97
	Fruit	$\hat{y}$ = 0.7/1 + exp(-(x - 147)/16))	0.94	$\hat{y}$ = 2.3/1 + exp(-(x - 141)/23))	0.92
Mg	Shoot	$\hat{y}$ = 2.6/1 + exp(-(x - 148)/26))	0.95	$\hat{y}$ = 6.1/1 + exp(-(x - 96)/15))	0.97
	Fruit	$\hat{y}$ = 4.0/1 + exp(-(x - 149)/28))	0.97	$\hat{y}$ = 9.4/1 + exp(-(x - 104)/16))	0.95
S	Shoot	$\hat{y}$ = 1031/1 + exp(-(x - 151)/22))	0.96	$\hat{y}$ = 2630/1 + exp(-(x - 114)/17))	0.93
	Fruit	$\hat{y}$ = 1.1/1 + exp(-(x - 142)/10))	0.90	$\hat{y}$ = 2.4/1 + exp(-(x - 122)/14))	0.85
B	Shoot	$\hat{y}$ = 16.7/1 + exp(-(x - 153)/18))	0.97	$\hat{y}$ = 49.4/1 + exp(-(x - 111)/17))	0.95
	Fruit	$\hat{y}$ = 6.0/1 + exp(-(x - 154)/4))	0.94	$\hat{y}$ = 11.7/1 + exp(-(x - 126)/13))	0.85
Cu	Shoot	$\hat{y}$ = 15.2/1 + exp(-(x - 145)/28))	0.96	$\hat{y}$ = 17.1/1 + exp(-(x - 100)/17))	0.90
	Fruit	$\hat{y}$ = 3.6/1 + exp(-(x - 149)/10))	0.92	$\hat{y}$ = 6.5/1 + exp(-(x - 122)/16))	0.85
Fe	Shoot	$\hat{y}$ = 544.0/1 + exp(-(x - 149)/33))	0.94	$\hat{y}$ = 1155.7/1 + exp(-(x - 130)/32))	0.98
	Fruit	$\hat{y}$ = 195.4/1 + exp(-(x - 154)/4))	0.93	$\hat{y}$ = 737.6/1 + exp(-(x - 182)/21))	0.98
Mn	Shoot	$\hat{y}$ = 68.3/1 + exp(-(x - 157)/17))	0.97	$\hat{y}$ = 82.1/1 + exp(-(x - 126)/21))	0.96
	Fruit	$\hat{y}$ = 10.4/1 + exp(-(x - 155)/4))	0.93	$\hat{y}$ = 19.3/1 + exp(-(x - 132)/10))	0.88
Zn	Shoot	$\hat{y}$ = 56.3/1 + exp(-(x - 142)/18))	0.93	$\hat{y}$ = 70.0/1 + exp(-(x - 112)/20))	0.94
	Fruit	$\hat{y}$ = 9.0/1 + exp(-(x - 151)/4))	0.90	$\hat{y}$ = 18.7/1 + exp(-(x - 124)/13))	0.86

Table 3. Maximum accumulation (MA), maximum daily accumulation rate (Mdar), point of maximum daily accumulation rate (X_{Mdar}), point of the minimum curve (CP_{min}), maximum (CP_{max}) of dry matter (DM), and nutrients in the shoot and fruit of physalis grown in two sites (DTA: Diamantina and SJE: São João Evangelista).

Variable	Site	MA		MDAR		X_{MDAR}		CP_{min}		CP_{max}	
		Shoot	Fruit	Shoot	Fruit	Shoot	Fruit	Shoot	Fruit	Shoot	Fruit
		kg ha^{-1}		kg ha^{-1} dia^{-1}				DAP			
DM	DTA	1128.6	406.7	12.88	25.39	151	154	107	146	195	162
	SJE	2629.7	677.6	38.83	12.15	114	126	80	98	148	154
N	DTA	27.9	7.0	0.23	0.22	146	147	86	131	206	163
	SJE	40.0	12.0	0.56	0.27	103	135	67	113	139	157
P	DTA	1.7	1.2	0.02	0.03	153	153	113	137	193	169
	SJE	5.7	3.5	0.09	0.04	102	117	74	87	130	147
K	DTA	21.7	6.23	0.20	0.16	149	147	95	127	203	167
	SJE	29.0	7.9	0.43	0.18	98	135	64	113	132	157
Ca	DTA	5.3	0.7	0.04	0.01	142	147	68	115	216	179
	SJE	13.5	2.3	0.15	0.03	108	141	62	95	154	187
Mg	DTA	2.6	0.3	0.03	0.01	148	138	96	106	200	170
	SJE	6.1	1.6	0.10	0.03	96	122	66	92	126	152
S	DTA	4.0	1.1	0.04	0.03	149	142	93	122	205	162
	SJE	9.4	2.4	0.15	0.04	104	122	72	94	136	150
		g ha^{-1}		g ha^{-1} dia^{-1}				DAP			
B	DTA	16.7	6.0	0.23	0.38	153	154	117	146	189	162
	SJE	49.4	11.7	0.71	0.23	111	126	77	100	145	152
Cu	DTA	15.2	3.6	0.14	0.09	145	149	89	129	201	169
	SJE	17.1	6.5	0.25	0.10	100	122	66	90	134	154
Fe	DTA	544.0	195.4	4.14	12.20	149	154	83	146	215	162
	SJE	1155.7	737.6	9.07	8.82	130	182	66	140	194	224
Mn	DTA	68.3	10.4	1.01	0.52	157	155	123	147	191	165
	SJE	82.1	19.3	0.98	0.48	126	132	84	112	168	152
Zn	DTA	56.3	9.0	0.79	0.52	142	151	106	143	178	159
	SJE	70.0	18.7	0.88	0.36	112	132	72	98	152	150

The sigmoidal behavior of the accumulation of DM and nutrients in the plants (Figure 2 and Table 2) indicates that physalis is a species that uptakes nutrients throughout the growth cycle, with the availability

of nutrients in the soil being essential for absorption by the roots. Specifically, to meet the nutritional requirements of the crop, nutrients must be available in the soil in required amounts, shape, and times throughout the cycle (Fageria & Moreira, 2011).

The DM and nutrient accumulations in shoot were higher at SJE than at DTA (Figure 2 and Table 2). The accumulations started (CP_{min}) and stabilized (CP_{max}) with high rates (Mdar) that began (X_{Mdar}) earlier at SJE (Table 3). This is related, above all, to the occurrence of higher temperatures at SJE in comparison to DTA (Figure 1). The higher temperatures occurring at SJE (Figure 1b) results in greater metabolic activity (Taiz & Zeiger, 2017) in plants and, consequently, greater speed of accumulation of DM and nutrients by increasing the accumulation rates (Mdar; Table 3). Temperature has a direct influence on the regulatory processes of plants, interfering with the speed of enzymatic reactions and, consequently, photosynthetic and respiratory rates (Taiz & Zeiger, 2017). The occurrence of high temperatures favors ion uptake by the roots. Elevated temperatures increase the ion transport processes in the soil solution to the roots as well as the penetration of ions into the apparent free space via the apoplast, stimulate the ion uptake in the root cells, and favor transport in the xylem (Marschner, 2012).

DM accumulation differed between shoot and fruit at both cultivation sites (Table 3). The greater accumulation of DM in fruit at DTA reflects the temperatures between 13 and 20ºC (Figure 1) that occurred during the cultivation cycle at this site. Physalis shows better growth and development in regions with annual temperatures between 13 and 18ºC (Fischer & Lüdders, 2002), and mild climatic conditions with a temperature of approximately 14ºC promotes flowering, fruiting, and sprouting (Lima et al., 2010). Conversely, plants grown at SJE had higher accumulations of DM in shoot (Table 3) promoted by elevated temperatures above 20ºC (Figure 1) throughout the cultivation. Temperatures at SJE were high resulting in better growth and development of physalis (Fischer & Lüdders, 2002), which were provided by greater metabolic activity in the plants (Taiz & Zeiger, 2017) which resulted in high accumulation rates (Mdar) of DM (Table 3), stimulating the vegetative growth of the plants. The cultivation of physalis at sites with high temperatures close to 30ºC tends to favor vegetative growth (Lima et al., 2010). However, the development of physalis can be greater in soil conditions with high fertility and greater water retention and a climate of good rainfall and high temperatures such as the edaphoclimatic conditions at SJE. These results suggest that physalis is responsive to increased availability of nutrients in the soil despite being a plant considered to be rustic (Muniz et al., 2014), which grows in different types of soil and requires low fertilization. Thus sufficient nutrition can result in adequate growth and crop yield in physalis (Torres et al., 2015).

Temperatures that occurred at DTA (Figure 1) were favorable for better reproductive growth to the detriment of the vegetative growth of the plants. This condition increased the accumulation rate (Mdar) of DM of the fruit (Table 3), that is, the rate of fruiting of the plants increased. The increase in the DM of the fruit resulted in similar X_{Mdar} for nutrients in shoot and fruit (Table 3). Thus, the nutrients were translocated to the fruit of physalis, as can be seen by the similar rates of nutrient accumulation in the fruit and shoot (Table 3). Physalis shows increased DM in fruit and greater need for nutrient absorption in the reproductive stage of growth when there is significant increase in the rate of fruiting (Salazar et al., 2008), as fruits are important for plants, and providing nutrients for their development is priority (Taiz & Zeiger, 2017). Temperatures close to 30ºC tend to favor vegetative growth (Lima et al., 2010). Thus, the high temperatures at SJE (Figure 1b) favored the vegetative growth of physalis plants. Under these conditions, the Mdar of DM increased, resulting in higher rates of accumulation (Mdar) of nutrients in shoot in comparison to the accumulation rates (Mdar) in fruit (Table 3). Therefore, the nutrients were accumulated first in the shoot and were then translocated to complete the processes of formation of the fruit, which reflects the earlier occurrence of Mdar in shoot compared to fruit (Table 3).

In the shoot, the X_{Mdar} corresponded to the period of greatest demand by the plant for nutrients, which occurred earlier at SJE in comparison to DTA (Table 3).The recommended time of nutrient application could be considered the time (CP_{min}) when there is a requirement for nutrients to be available in the soil to meet the greater demand at the time of maximum daily accumulation rate. Fertilization aims at supplying adequate nutrition to the crops. It is necessary to understand the basic principles of nutrient dynamics in the soil (Fageria & Moreira, 2011) as it can influence the time of nutrient application. Therefore, considering the dynamics of N and K in the soil, it would be ideal to apply a small part of N and K at the time of planting and again as cover fertilization when accumulations begin to significantly increase (CP_{min}) around 64 DAP at SJE and 86 DAP at DTA, so that there is adequate availability of N and K during the critical phases when these

nutrients are in demand. This practice is especially beneficial in soils with a higher probability of leachate losses (Fageria & Moreira, 2011).

Further, it appears that, despite P being absorbed practically throughout growth cycle of the plant (Figure 2c), the greatest demand occurred at X_{Mdar} at 102 DAP at SJE and 153 DAP at DTA (Table 3). However, because much of the P added to the soil becomes immobile or unavailable because of the specific adsorption of P (Fink, Inda, Tiecher, & Barrón, 2016), it is understandable to apply all P at the time of planting. The supply at the beginning of the cycle is very important in the early stages of development of physalis, which concentrates on the vegetative parts and is redistributed to the fruit at the time of fruiting (Parra et al., 2015). On the other hand, the times of greatest demand for Ca and Mg started from 62 DAP (Table 3). The cheapest way to supply Ca and Mg to the crop is through liming using limestone (Braga Neto et al., 2019). As for S, maximum absorption was seen from 104 DAP (Table 3). If sources of phosphate fertilizers such as simple superphosphate, or even ammonium sulphate are applied in coverage, this would certainly meet the needs of physalis, as the quantities accumulated by the plants were between 4.0 (DTA) and 9.7 (SJE) kg ha^{-1} of S (Table 3).

Based on the time of greatest demand for micronutrients, it appears that when applications of micronutrients in coverage are indicated, it is convenient to carry it out at the time of CP_{min}. Our results suggest that applications at 77-117 DAP with B, 66-123 DAP with Fe and Mn, and at 72 DAP with Cu and Zn (Table 3), is ideal to ensure that there is adequate availability of these micronutrients during the critical accumulation phase. B and Zn are the micronutrients that are most often deficient in Brazilian soils, and their deficiency is very common in plants of economic interest (Fageria & Moreira, 2011). The supply of B and Zn may be combined with N in coverage, since the time (CP_{min}) of application of N coverage (64-86 DAP) is before the greatest demand for B (77-117 DAP) and Zn (72-106 DAP) for physalis (Table 3). Foliar fertilization can supply all micronutrients for physalis after undertaking leaf diagnosis, where leaf sampling is carried out at the full flowering stage of the plants (Silva et al., 2018), which occurred at 60 DAP, where leaf sampling is before the time (X_{MDAR}) of greater demand for micronutrients by physalis (Table 3).

Macronutrients were accumulated in greater quantity by physalis in the following order: N > K > Ca > S > Mg > P (Table 3), which reflects the nutritional requirements of the plant. In general, most cultures show the following order of requirement of macronutrients: N > K > Ca > Mg > P ⩾ S (Malavolta, 2006), with only the inversion of Mg in relation to S. On the other hand, the sequence in decreasing order of accumulation of macronutrients in fruit was N > K > P > S > Ca > Mg (Table 3). Although tendency for higher requirements of N and K, was maintained, the requirement of other macronutrients was related to the mobility of the nutrients in the plant (Marschner, 2012) and the requirement of the physalis (Silva et al., 2017).

N is one of the macronutrients most required by physalis (Martínez et al., 2008; Torres et al., 2015; Parra et al., 2015) as also K. Deficiency in K results in growth reductions (Marschner, 2012). Also, it is responsible for flowering and fixation of fruit (Muniz et al., 2014), and the deficiencies of N and K affect the weight of the fruit (Martínez et al., 2008).

The accumulation of P and S in the shoot and fruit showed that P was less required by physalis than S, and that P and S accumulated more in fruit than in shoot (Table 3). P is one of the primary macronutrients required by physalis (Torres et al., 2015; Parra et al., 2015). Being a mobile nutrient in the phloem they tend to accumulate in fruit (Marschner, 2012) resulting in them having higher P concentration (Díaz et al., 2011). S was the macronutrient that most limited the growth of physalis (Silva et al., 2017). Although S is considered to be relatively less mobile in the plant, in comparison to P, the concentration of S was higher in fruits. This is likely because S in the form of sulfate is transported in both xylem and phloem, and is readily interchangeable between these pathways (Marschner, 2012).

The low Ca accumulation in fruit in comparison to shoot (Table 3) is because reserve organs, such as fruit, need lower concentrations of Ca for optimal growth (Marschner, 2012). An adequate availability of Ca in the soil solution increases the Ca concentration in leaves, but there is no redistribution to the fruit due to the low mobility in the phloem (Malavolta, 2006). As fruit show low transpiration, the amount of Ca transported to this organ by the xylem is low. The proper way to meet the greater requirement of Ca than Mg would be to use limestone for liming (Braga Neto et al., 2019).

Our results show that the maximum N extracted by physalis, reached 28 at DTA and 40 kg ha^{-1} at SJE (Table 3), which was 56 to 80% of the amount of N applied (50 kg ha^{-1}). This demonstrates the high demand for N by physalis (Martínez et al., 2008; Torres et al., 2015; Parra et al., 2015). In the case of P, the initial concentration in the soil was low (Table 1), and the extraction of P by the plants was between 1.5 at DTA and

5.7 kg ha^{-1} at SJE (Table 3). Without considering the P adsorption process in soils (Fink et al., 2016) and the amount of P already present in the soil before planting fertilization, it appears that the extraction of P was between 4 and 14% of the amount of P applied (34 kg ha^{-1}). These results demonstrate that the extraction of P is small, confirming the low demand for P by physalis (Torres et al., 2015; Parra et al., 2015) and by most cultures (Malavolta, 2006). It was noted that the extractions of K were 22 and 29 kg ha^{-1} at DTA and SJE, respectively (Table 3). Thus, physalis extracted between 26 and 35% of the applied amount of K (83 kg ha^{-1}), indicating the lowest requirement in comparison to N (Torres et al., 2015; Parra et al., 2015).

The amount of micronutrients accumulated by physalis was the same in the shoot and fruit due to the low mobility of the micronutrients in the phloem (Marschner, 2012). The order of accumulation was Fe > Mn > Zn > B > Cu (Table 3), which reflected the crop requirement. Most crops generally obey this order of micronutrient requirements (Malavolta, 2006).

Compared to other micronutrients, Fe limits development of physalis the most (Moschini et al., 2017; Silva et al., 2017). The marked deficiency of Fe causes a reduction in the size and number of leaves, consequently resulting in less plant growth and development (Marschner, 2012). The requirement for cationic micronutrients, especially Fe, which participates in chlorophyll biosynthesis and in the formation of ferredoxin, can cause damage by oxidative stress, in photosystems I and II in chloroplasts (Tripathi et al., 2015). Cu, which is absorbed in small quantities, is the least limiting micronutrient for growth (Silva et al., 2017). It is absorbed in small amounts, being considered a relatively mobile nutrient in well-nourished plants, and can be easily transported (Marschner, 2012). Even though it is a nutrient necessary for plants, compared to Fe, the amount of Cu required by physalis is lower (Silva et al., 2017). The other micronutrients limited the growth of physalis in the following order: B > Mn > Zn (Silva et al., 2017).

Conclusion

Biomass production and nutrient accumulation was higher in the edaphoclimatic conditions at SJE compared to the conditions at DTA. Macronutrient accumulation was in the following order: N > K > Ca > S > Mg > P in shoot and N > K > P > S > Ca > Mg in fruit. Micronutrient accumulation in both shoot and fruit was in the following order: Fe > Mn > Zn > B > Cu. Cover fertilization for N and K should be performed 64 and 86 days after planting of physalis at SJE and DTA, respectively.

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