

# Accumulation and distribution of calcium, magnesium, and sulfur in potato (*Solanum tuberosum* Group Andigenum) cultivars Diacol Capiro and Pastusa Suprema

Acumulación y distribución de calcio, magnesio y azufre en cultivares de papa (*Solanum tuberosum* grupo Andigenum) Diacol Capiro y Pastusa Suprema

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## ABSTRACT

The potato crop has a high response to nutrient application; however, knowledge about requirements and management of calcium (Ca), magnesium (Mg), and sulfur (S) is scarce. It is important to study the accumulation, as well as translocation and use efficiencies, of these nutrients, considering the influence of genotype and environment variables. The objective of this research was to establish the nutrient curves for accumulation, as well as for translocation, use, and recovery efficiencies, of Ca, Mg and S for two potato cultivars of the Andigenum Group in two production cycles (2013-2016) and two localities (Chocontá and Facatativá) with contrasting edaphoclimatic conditions. Diacol Capiro and Pastusa Suprema cultivars were evaluated under two fertilization regimes (0 and 100% of the recommended dose for all essential nutrients). Data on fresh and dry weight, and Ca, Mg, and S content were recorded at five sampling moments, from main stem formation to tuber maturation. The highest accumulation of Ca, Mg, and S was obtained in Facatativá, however the highest translocation, use and recovery efficiencies of nutrients were obtained in Chocontá. Capiro showed higher sink strength, with a higher translocation efficiency compared to Suprema. Nutrient accumulation in tubers ( $\text{kg ha}^{-1}$ ) followed the order of Ca (147) > Mg (66) > S (52), while translocation efficiencies at harvest were S (44%) > Mg (32%) > Ca (6%). Cultivars had different patterns of accumulation, translocation, and Ca, Mg, and S use, which also varied with locality. Capiro was better adapted to high fertility soil conditions and Suprema had better performance in low fertility soils.

**Key words:** absorption curves, translocation efficiency, nutrition use efficiency, recovery efficiency.

## RESUMEN

El cultivo de papa presenta una alta respuesta al manejo de la nutrición; sin embargo, el conocimiento sobre los requerimientos y manejo del calcio (Ca), magnesio (Mg) y azufre (S) es escaso. Es necesario profundizar en los procesos de acumulación, traslocación y uso eficiente de estos nutrientes teniendo en cuenta la influencia de variables como genotipo y ambiente. El objetivo de la presente investigación fue establecer las curvas de absorción, eficiencia de traslocación, uso eficiente y eficiencia de recuperación de Ca, Mg y S en dos cultivares de papa del Grupo Andigenum en dos ciclos (2013-2016) y dos localidades (Chocontá y Facatativá) con condiciones edafoclimáticas contrastantes. Se evaluaron los cultivares Diacol Capiro y Pastusa Suprema bajo dos regímenes de fertilización (0 y 100% de la dosis recomendada para todos los nutrientes esenciales). Se registró información de peso fresco, seco y contenido de Ca, Mg y S en cinco puntos de muestreo, desde la formación de tallos hasta la maduración de los tubérculos. La mayor acumulación de Ca-Mg-S se dio en Facatativá; sin embargo, la mayor eficiencia de traslocación, uso eficiente y recuperación de nutrientes se obtuvo en Chocontá. Capiro mostró una mayor fuerza vertedero al presentar una mejor eficiencia de traslocación respecto a Suprema. La acumulación de nutrientes ( $\text{kg ha}^{-1}$ ) siguió el orden de Ca (147) > Mg (66) > S (52), mientras la eficiencia de traslocación en cosecha fue de S (44%) > Mg (32%) > Ca (6%). Los cultivares evaluados presentaron procesos diferentes de acumulación, traslocación y uso eficiente de Ca-Mg-S, los cuales también variaron con la localidad. Capiro tuvo mejor adaptación a las condiciones de suelo de alta fertilidad, mientras Suprema mostró mejor desempeño en condiciones de baja fertilidad.

**Palabras clave:** curvas de absorción, eficiencia de traslocación, uso eficiente de nutrientes, eficiencia de recuperación.

## Introduction

Negative impacts on crop yield and quality are expected in the coming years due to temperature and precipitation

changes associated with climate change (Hameed *et al.*, 2018; Handayani *et al.*, 2019). For the years 2040 to 2069, potato crop yield is estimated to decrease by 18-32% (Dahal *et al.*, 2019). Potato has great relevance for global food

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security due to its nutritional and yield qualities (Gaj *et al.*, 2020; Handayani *et al.*, 2019). In addition, with a projected increase of 30% in the world population by the year 2050, there is a need to increase food production. This scenario presents a challenge requiring more sustainable and efficient crop systems (Dahal *et al.*, 2019).

The potential yield of potato crop is high ( $> 40 \text{ t ha}^{-1}$ ); nevertheless it depends on crucial factors like nutrient management (Campos & Ortiz, 2020). Differences in edaphoclimatic conditions between localities, adaptation of cultivars to these localities, and specific nutritional requirements of each cultivar, are causes of heterogeneity in yield and tuber quality (Gaj *et al.*, 2020; Villamil *et al.*, 2005). It is important to define the specific nutrient requirements for each cultivar in a locality to improve yield, increase fertilizer efficiency, and reduce the environmental impact of this practice (Dahal *et al.*, 2019).

Adequate management of calcium (Ca), magnesium (Mg), and sulfur (S) can increase crop production, improve quality, and reduce the incidence of phytosanitary problems and physiological disorders such as hollow or cracked heart of the tubers (Wendimu Seifu & Deneke, 2017). Cultivars of Andigenum Group are among some of the most widely grown in Colombia, nevertheless there is limited information about uptake, translocation, and use of the mineral elements Ca, Mg, and S for these cultivars. Due to their low mobility in phloem, symptoms of nutritional deficiencies of Ca and S appear in the youngest leaves (Hamdi *et al.*, 2015), while deficiency symptoms of Mg are expressed in the mature leaves of the plants (Senbayram *et al.*, 2015). The accumulation and translocation of calcium, magnesium and sulfur are affected by soil and weather factors such as pH, CEC, soil texture, organic matter, microbial activity, rainfall regime, temperature, among others (Castro & Gómez, 2013). Additionally, it is important to consider the source-sink relationship in each cultivar, which determines the accumulation of dry matter and nutrients in the tubers (Bender *et al.*, 2015).

There are different approaches to establish the nutritional requirements for a crop. Potato growers often rely on general fertilizations, traditionally used or reported in literature. However, this information does not consider factors like edaphoclimatic conditions per location, cultivar features, or productive cycle (Silva *et al.*, 2020). Accumulation and translocation curves of nutrients are models that describe the amount of a given nutrient that is translocated to the tuber through the productive cycle. These curves allow for specific nutritional corrections at any moment of the

production cycle (Duarte *et al.*, 2019; Silva *et al.*, 2020). Additionally, nutrient management should consider the measurement of the nutrient use efficiency, *i.e.*, the amount of tubers produced by nutrient unit, as well as nutrient recovery efficiency, *i.e.*, the amount of nutrient applied that the plants actually uptake (Lemaire *et al.*, 2019).

The objective of the present research was to establish curves for accumulation, as well as for translocation, use and recovery efficiencies of Ca, Mg, and S in two cultivars of potato (*S. tuberosum* Group Andigenum) in two localities of the Cundinamarca-Boyacá highlands in Colombia.

## Materials and methods

### Study site

This research was carried out in two localities representative of the production of potatoes in Colombia and with records of high yields ( $> 50 \text{ t ha}^{-1}$ ): Facatativá with high fertility (Andic Eutrudepts) and Chocontá with low fertility (Humic Dystrudepts) (Castellanos Ruiz *et al.*, 2022). In each locality, two production cycles were evaluated between the years 2013-2016, each with a total duration of 150-160 d after planting (DAP). Climatic variables and soil characteristics for the arable layer (0-30 cm) were monitored and recorded in each locality and cycle, prior to the establishment of the trial. Details of climatic variables and soil characteristics by locality and crop cycle can be found in Gómez *et al.* (2019).

### Experimental design and crop management

Four experiments were conducted across different seasons using a split-plot design with four replicates distributed in randomized complete blocks. The main plot was the cultivar (Diacol Capiro and Pastusa Suprema) and the subplot was the level of fertilization (0 and 100% of the recommended doses of macro and micronutrients). The 100% fertilization treatment corresponded to the full nutrient recommendation for each locality-cycle, established using the soil-plant balance method (Castro & Gómez, 2013) and the recommendation given by Gomez *et al.* (2019) (see detailed information in Castellanos Ruiz *et al.* (2022)), while the 0% treatment was unfertilized soil. The dose fractionation was carried out according to the historical management of the study sites (historical yields  $> 50 \text{ t ha}^{-1}$ ) as follows: N 55% at sowing and 45% at 45 DAP; P 80% at sowing, and 20% at 45 DAP; K 12% at sowing and 88% at 45 DAP; for Ca, Mg, S, 63% was applied at sowing and 37% at 45 DAP. Experimental units of 5 m x 10 m were established, with a distance between rows of 1 m and 0.37 m between plants, for a density of 27,000 plants  $\text{ha}^{-1}$ . Tubers averaging

70 g were used as seed and were sown manually. Each plot had a total of 135 plants. Phytosanitary management of the crop was carried out according to local practices.

### Sampling and measurements

Five destructive samplings were carried out at five phenological stages (Valbuena *et al.*, 2009) (Tab. 1). Four plants were harvested per experimental unit in each sampling moment; leaves, stems and tubers were removed, and their fresh weights were recorded separately. To quantify mineral nutrient content in each organ, plant material was washed with deionized water, the same organs from the four plants were mixed, and a subsample of 200 g was separated and dried in an oven at 70°C to constant weight to determine the dry weight (Gómez *et al.*, 2019). For chemical analysis, the total concentration of Ca, Mg, and S per organ was determined according to IGAC (2006). The total content of each nutrient was estimated by multiplying the concentrations of nutrients in the organs (g 100 g<sup>-1</sup> dry weight) by the amount of dry biomass accumulated per organ at each phenological stage (Abdallah *et al.*, 2016).

**TABLE 1.** Sampling stages in relation to days after planting (DAP) and corresponding phenological stages.

Stage	DAP	Phenological stage
I	50-55	Formation of primary stems
II	70-75	Formation of secondary stems and initial tuberization
III	90-100	Flowering, maximum tuberization and beginning of tuber filling
IV	120-125	End of flowering, tuber filling
V	150-160	Leaf senescence, maximum filling, and tuber maturation

### Statistical analysis

For each variable, an analysis of variance (ANOVA) was performed using the PROC GLM procedure (SAS Institute, 2017). When significant differences were identified, a comparison test of means between treatments was performed using the Tukey-Kramer test ( $P < 0.05$ ). All statistical analyses were performed using SAS 9.4 software (SAS Institute, 2017) and the graphs were constructed using ggplot2 (Wickham, 2016).

### Nutrient accumulation curves

Total (ACTot) and tuber (ACTub) nutrient accumulation curves were developed from the concentration values of the nutrients per unit dry weight at each sampling stage. The ACTot and ACTub models were fitted using the NLIN procedure in SAS (SAS Institute, 2017). For ACTub, the model proposed by Yin *et al.* (2003) was fitted (Eq. 1), where  $C_{tub}$  represents the concentration of the nutrient in the

tuber.  $C_{max}$  is the maximum concentration of the nutrient obtained at time  $t_e$  (end of period growth),  $t_b$  is the start time of the growth period, and  $t_m$  is the time corresponding to the highest accumulation rate of the nutrient. In contrast, for ACTot, the Yin *et al.* (2003) model showed poor fit and low convergence. Therefore, the model proposed by Ziadi *et al.* (2008) (Eq. 2) was used instead. In this model,  $C$  represents the total accumulation of the nutrient,  $W$  is the total dry biomass, and  $a$  and  $b$  are fitting coefficients. Due to the difference between the models, the independent variables were days after planting for the ACTub model and total dry biomass for the ACTot model. Confidence intervals at 95% and the standard error of the coefficients were established to evaluate nutrient accumulation between cultivars and localities.

$$C_{tub} = C_{max} \left( 1 + \frac{t_e - t_b}{t_e - t_m} \right) \left( \frac{t_b}{t_e} \right)^{\frac{t_e}{t_e - t_m}} \quad (1)$$

with  $0 < t_m < t_e$

$$C = aW^b \quad (2)$$

### Growth curve and nutrient accumulation by phenological stage

A three-parameter logistic growth model was fitted (Ritz *et al.*, 2015) to calculate the growth curve as a function of days after planting (Eq. 3), where  $b$ ,  $d$  and  $e$  are the model coefficients and  $x$  is days after planting. Using the growth curve and the total accumulation model (Eq. 2), values for nutrient accumulation by phenological stage were established for the plants. Nutrient accumulation was also calculated for the tuber based on the tuber accumulation model (Eq. 1).

$$W = c + \frac{d-c}{1 + \exp(b(\log(x) - \log(e)))} \quad (3)$$

### Translocation efficiency

Translocation efficiency (CaTE, MgTE, STE) was calculated by dividing the accumulation of nutrients in the tubers ( $N_{tub}$ ) (kg ha<sup>-1</sup>) by the total accumulation of nutrients in the plant ( $N_{upt}$ ) (kg ha<sup>-1</sup>) at each sampled phenological stage (Eq. 4). The translocation efficiency curve was fitted using the NLIN procedure in SAS (SAS Institute, 2017), adjusting it to a logarithmic function as proposed by Gómez *et al.* (2019).

$$\text{Nutrient TE} = (N_{tub} / N_{upt}) \times 100\% \quad (4)$$

### Acquisition or recovery efficiency

The fertilizer nutrient recovery efficiency, or acquisition efficiency, for Ca (RFCa), Mg (RFMg), and S (RFS) was

calculated using Equation 5, as proposed by Gómez *et al.* (2018), where  $E_{t1}$  is the extraction of nutrients by tubers in fertilized soils ( $\text{kg ha}^{-1}$ ) and  $E_{t0}$  is the extraction of nutrients by tubers in unfertilized soils ( $\text{kg ha}^{-1}$ ).

$$\text{RF} = \frac{E_{t1} - E_{t0}}{\text{amount of nutrients supplied with the fertilizer}} \times 100 \quad (5)$$

### Nutrient use efficiency

Nutrient use efficiency (UE) of Ca (CaUE), Mg (MgUE) and S (SUE) in the tubers was calculated as the dry matter accumulated in the tuber/total kg of the extracted nutrient, as proposed by Poljak *et al.* (2011).

### Ethical considerations

The activities in the laboratory and the management of chemical and biodegradable waste were carried out according to the protocol of the Universidad Nacional de Colombia B-FT-15-003.033 and the Colombian Technical Guide 53-7 for the use of non-hazardous organic solid waste.

## Results

### Growth curves

Growth models were established based on the DAP for each cultivar-locality (Fig. 1). The models had a high level of fit, and no significant differences were found between localities or cultivars (Tab. 2). The accumulation of dry biomass was faster in Facatativá than in Chocontá, and Suprema showed greater and faster accumulation of biomass compared to Capiro. The highest accumulation of dry biomass occurred between 75-100 DAP, which coincided with the formation of secondary stems and the beginning of tuberization (stages I and II).

### Nutrient accumulation curves

For the total nutrient accumulation curves, significant differences were found between localities and in the locality x cultivar interaction for the three nutrients ( $P < 0.001$ ). A cultivar effect was observed on the accumulation of Mg and

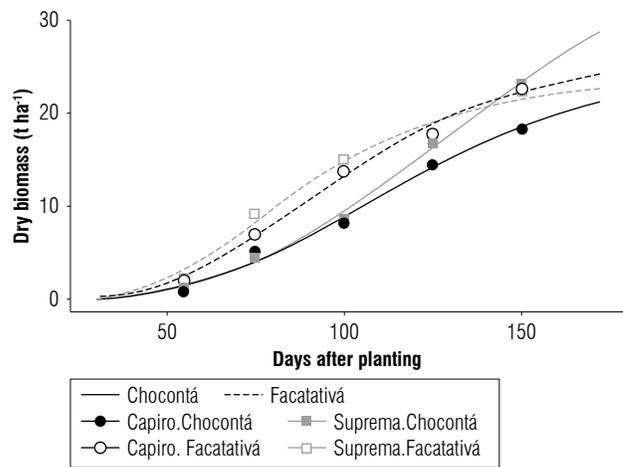


FIGURE 1. Growth model for Diacol Capiro and Pastusa Suprema potato cultivars in two localities with contrasting edaphoclimatic conditions.

S, and Ca. The Mg accumulation models showed significant differences between the localities (coefficient  $a$  and  $b$  with  $P < 0.05$ ) for both cultivars (Tab. 3, Fig. 2). For S, only the Capiro accumulation model showed differences between localities. Between cultivars, significant differences were observed in the models for Chocontá (coefficients  $a$  and  $b$  with  $P < 0.05$ ); the accumulation of Ca and Mg was greater in Suprema (Fig. 2). At a dry biomass of  $25 \text{ t ha}^{-1}$ , Capiro and Suprema presented the highest accumulation of Ca ( $223$  and  $185 \text{ kg ha}^{-1}$ ) and Mg ( $86$  and  $78 \text{ kg ha}^{-1}$ ) in Facatativá, without significant differences between cultivars. In Chocontá, Suprema had significantly higher accumulation of Ca and Mg, with  $50\%$  and  $59\%$  more, respectively, compared to Capiro. Sulfur accumulation in Capiro was higher in Facatativá ( $59 \text{ kg ha}^{-1}$ ), while in Suprema, no significant differences were found between localities.

The data collected for tuber nutrient accumulation demonstrated the effect of the cultivar and locality x cultivar interaction ( $P < 0.001$ ). The accumulation models of Ca, Mg and S in the tubers showed no significant differences between cultivars or localities; however, a lower accumulation of Mg and S was observed for Suprema in Facatativá (Tab. 4). The models indicated that the accumulation rate of Mg and S in the Capiro tuber in Chocontá decreased

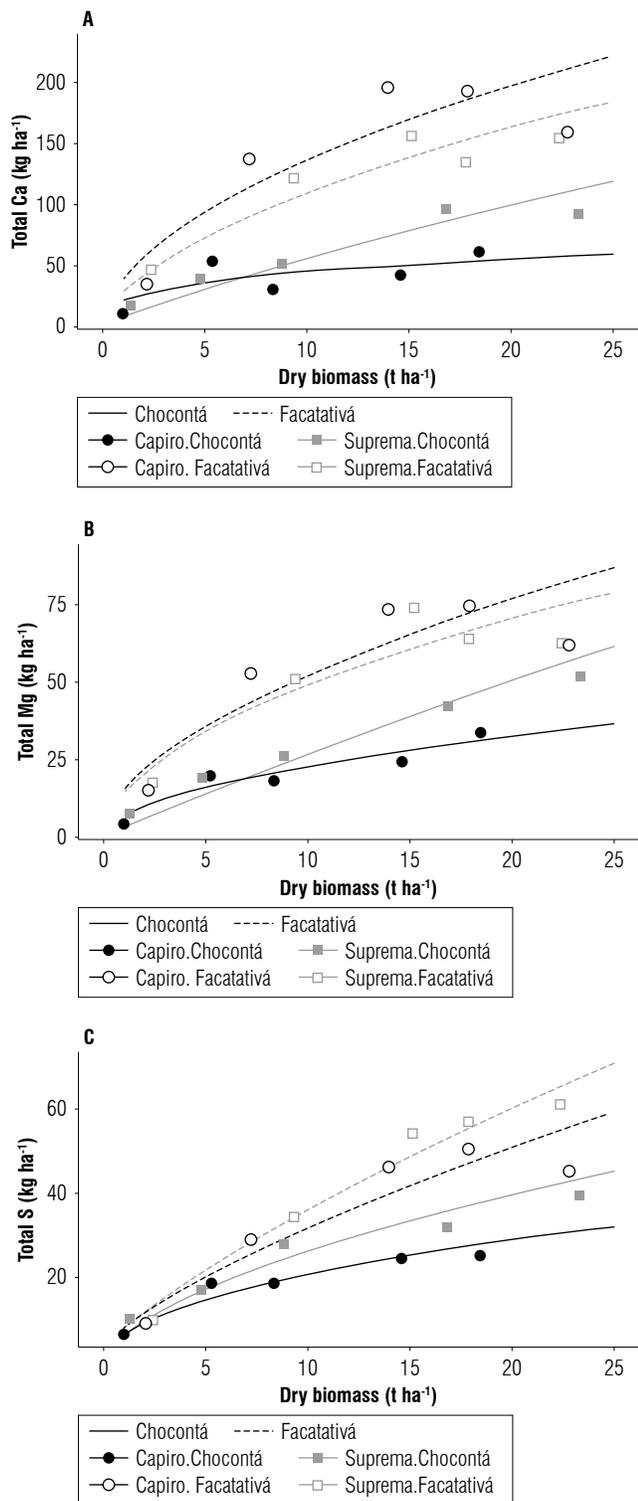
TABLE 2. Growth models coefficients for potato cultivars Diacol Capiro and Pastusa Suprema in two localities.

Cultivar	Locality	b	d	e	SE b	SE d	SE e
Capiro	Facatativá	-3.59	28.07	102.69	0.66 ns	4.21 ns	22.40 ns
	Chocontá	-3.38	28.70	125.67	0.70 ns	7.96 ns	10.82 ns
Suprema	Facatativá	-3.76	24.62	89.32	0.77 ns	2.98 ns	8.07 ns
	Chocontá	-3.36	47.22	150.81	0.71 ns	21.10 ns	38.54 ns

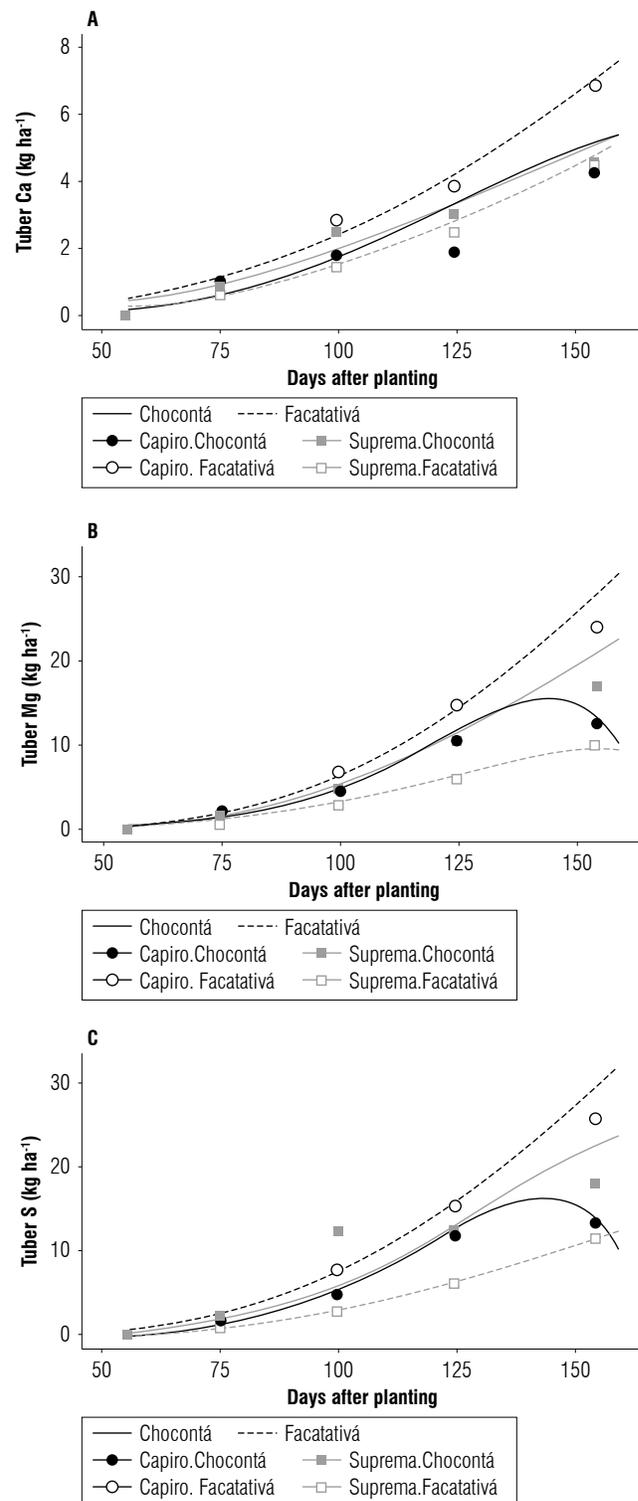
ns: no significant differences between cultivars or localities. SE: Standard error. b, d, and e: Fitted equation coefficients.

towards the end of the cycle (Fig. 3). Based on the models, the accumulation of Ca, Mg, and S in the tuber and their proportion by phenological stage was established (Tab. 5).

The highest accumulation of nutrients coincided with the phenological stages of maximum tuberization and tuber filling (stages III and IV).



**FIGURE 2.** Calcium (A), magnesium (B), and sulfur (C) total accumulation curves in potato cultivars Diacol Capiro and Pastusa Suprema in two localities with contrasting edaphoclimatic conditions.



**FIGURE 3.** Calcium (A), magnesium (B), and sulfur (C) tuber accumulation curves in potato cultivars Diacol Capiro and Pastusa Suprema in two localities with contrasting edaphoclimatic conditions.

**TABLE 3.** Ca, Mg, and S total accumulation curves coefficients for Diacol Capiro and Pastusa Suprema cultivars in two localities with contrasting edaphoclimatic conditions.

Nutrient	Locality	Cultivar	Curve ( $N_{ac} = aW^b$ )	RMSE	CI (a) 95%	CI (b) 95%	SE a	SE b
Calcium	Chocontá	Capiro	21.84W <sup>0.31</sup>	26.24	11.35-32.32	0.12 -0.50	5.26 *, **	0.10 *
		Suprema	8.27W <sup>0.83</sup>	28.22	3.30 -13.24	0.63 -1.04	2.49 *, **	0.10 *
	Facatativá	Capiro	40.44W <sup>0.53</sup>	44.78	24.58-56.30	0.39 -0.67	7.92 **	0.07 ns
		Suprema	29.53W <sup>0.57</sup>	37.14	16.09-42.96	0.41 -0.73	6.71 **	0.08 ns
Magnesium	Chocontá	Capiro	7.05W <sup>0.51</sup>	7.66	4.50 - 9.61	0.37 -0.64	1.28 *, **	0.07 *
		Suprema	3.50W <sup>0.89</sup>	11.91	1.61 -5.38	0.71- 1.07	0.94 *, **	0.09 *, **
	Facatativá	Capiro	14.72W <sup>0.55</sup>	18.78	8.29- 21.16	0.39 -0.70	3.21 **	0.08 ns
		Suprema	14.71W <sup>0.52</sup>	20.80	6.50 -22.91	0.32 -0.72	4.10 **	0.10 **
Sulfur	Chocontá	Capiro	7.27W <sup>0.46</sup>	4.93	5.55 -8.99	0.37 -0.55	0.86 ns	0.05 **
		Suprema	6.60W <sup>0.60</sup>	11.25	3.62 -9.58	0.43 -0.75	1.49 ns	0.08 ns
	Facatativá	Capiro	7.30W <sup>0.65</sup>	9.20	4.69 -9.91	0.53 -0.77	1.30 ns	0.06 **
		Suprema	6.76W <sup>0.73</sup>	8.80	4.44 -9.08	0.61 -0.85	1.16 ns	0.06 ns

\* Significant differences between cultivars at  $P < 0.05$ , \*\* significant differences between localities at  $P < 0.05$ , ns: No significant differences between cultivars or localities. RMSE: Root mean square error. CI: Confidence interval. SE: Standard error.

**TABLE 4.** Ca, Mg, and S tuber accumulation curves coefficients for Diacol Capiro and Pastusa Suprema cultivars in two localities with contrasting edaphoclimatic conditions.

Nutrient	Locality	Cultivar	cm	E	M	RMSE	SE cm	SE e	SE m
Calcium	Chocontá	Capiro	5.58	170.10	128.10	0.69	1.73 ns	34.07 ns	16.65 ns
		Suprema	6.73	202.80	136.40	0.95	7.67 ns	146.20 ns	72.44 ns
	Faca	Capiro	32.85	382.00	245.10	1.74	501.80 ns	2772.20 ns	1636.10 ns
		Suprema	6.43	195.00	142.80	1.24	12.29 ns	195.10 ns	110.20 ns
Magnesium	Chocontá	Capiro	15.50	144.60	120.50	2.10	0.88 ns	3.29 ns	2.38 ns
		Suprema	26.61	182.80	143.70	2.43	20.37 ns	62.20 ns	38.00 ns
	Facatativá	Capiro	40.25	193.20	151.30	6.40	102.60 ns	201.20 ns	129.00 ns
		Suprema	9.64	157.10	125.00	1.05	1.06 ns	13.49 ns	5.95 ns
Sulfur	Chocontá	Capiro	16.56	143.80	119.90	1.72	0.76 ns	2.17 ns	1.86 ns
		Suprema	24.83	170.00	134.90	3.53	12.56 ns	44.77 ns	24.81 ns
	Facatativá	Capiro	43.33	196.60	151.10	6.25	98.67 ns	193.50 ns	121.20 ns
		Suprema	13.44	175.70	138.50	1.12	6.36 ns	40.28 ns	23.37 ns

ns: No significant differences between locality or cultivar. cm, E and M: Equation coefficients. RMSE: Root mean square error. SE: Standard error.

### Nutrient translocation efficiency

An effect of the locality ( $P < 0.01$ ) was observed on the translocation efficiency of the nutrients, which was significantly higher in Chocontá than in Facatativá (Fig. 4). For Mg and S, an effect of the cultivar ( $P < 0.01$ ) was observed from 100 DAP in favor of Capiro. The translocation efficiency during the production cycle was fitted to a positive logarithmic model. From the beginning of tuberization (75 DAP), values progressively increased, reaching their maximum at harvest (155 DAP). Calcium showed the lowest translocation efficiency, with an average value of 5.5%, followed by Mg with 33.5% and S with 44.5%.

The models in Chocontá were significantly different from those in Facatativá (parameters  $a$  and  $b$  with  $P < 0.01$ ), except for the S model in Capiro, where there were no significant differences between the localities (Tab. 6). For the MgTE and STE models in Facatativá, significant differences were found between the cultivars (parameters  $a$  and  $b$  at  $P < 0.01$ ), with Capiro showing 57% and 67% higher translocation efficiency of Mg and S, respectively, at 155 DAP compared to Suprema. In Chocontá, there were no differences between the cultivars, in contrast to what was found in the total accumulation of nutrients. The Ca translocation efficiency did not differ between cultivars within the same locality.

**TABLE 5.** Forecast of total accumulation and in the tubers of Ca, Mg, and S by phenological stage for Diacol Capiro and Pastusa Suprema cultivars in two localities with contrasting edaphoclimatic conditions.

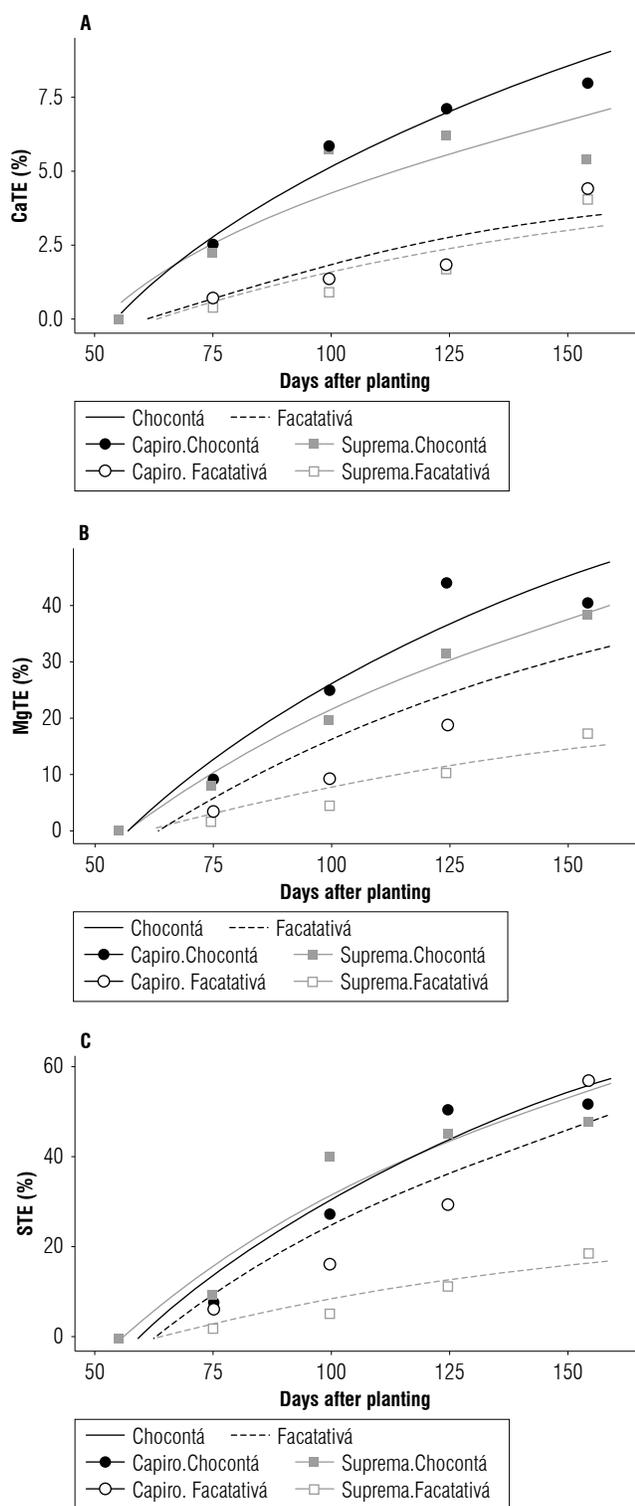
Cultivar	Locality	PS	DAP	AC total (kg ha <sup>-1</sup> )			ACTub (kg ha <sup>-1</sup> )			ACTub stage (%)		
				Ca	Mg	S	Ca	Mg	S	Ca	Mg	S
Capiro	Chocontá	I	0-55	25.5	9.1	9.2	0.0	0.0	0.0	0.0	0.0	0.0
		II	55-75	34.2	14.8	14.2	0.4	1.0	1.0	8.6	8.3	10.5
		III	75-100	43.3	21.7	20.0	1.1	3.7	4.0	32.0	40.1	32.3
		IV	100-125	49.7	27.3	24.7	1.6	6.9	7.5	65.5	77.9	80.2
		V	125-150	54.0	31.2	27.8	1.6	3.3	3.1	100	100	100
	Facatativá	I	0-55	68.4	25.4	13.9	0.0	0.0	0.0	0.0	0.0	0.0
		II	55-75	112.2	42.5	25.5	0.6	1.4	1.7	10.6	5.7	6.6
		III	75-100	159.8	61.3	39.4	1.3	4.3	4.8	31.4	22.9	24.8
		IV	100-125	191.4	73.9	49.1	1.8	8.0	8.5	61.2	54.9	56.7
		V	125-150	209.8	81.3	55.0	2.3	11.2	11.5	100	100	100
Suprema	Chocontá	I	0-55	11.9	5.2	8.6	0.0	0.0	0.0	0.0	0.0	0.0
		II	55-75	26.8	12.4	15.5	0.5	1.1	1.3	12.3	6.0	6.2
		III	75-100	53.6	26.0	25.5	1.0	3.4	3.9	35.8	23.8	25.2
		IV	100-125	84.3	42.2	35.4	1.4	6.2	7.1	66.5	56.5	59.3
		V	125-150	113.2	57.9	43.8	1.5	8.3	8.5	100	100	100
	Facatativá	I	0-55	59.6	27.9	16.6	0.0	0.0	0.0	0.0	0.0	0.0
		II	55-75	99.4	44.5	32.0	0.4	0.7	0.7	9.1	7.5	6.2
		III	75-100	137.6	59.9	48.5	0.9	2.0	2.0	30.0	29.5	24.8
		IV	100-125	159.1	68.4	58.4	1.4	3.4	3.5	61.8	66.2	58.1
		V	125-150	170.0	72.6	63.6	1.6	3.1	4.4	100	100	100

PS: Phenological stage. DAP: Days after planting. Total AC: Total accumulation. ACTub: Accumulation in the tubers. I: Stem formation, II: Beginning of tuberization, III: Flowering-maximum. Tuberization, IV: Filling of tubers-flowering cessation, V: Maximum filling-ripening of tubers.

**TABLE 6.** Ca, Mg, and S translocation efficiency models coefficients for Diacol Capiro and Pastusa Suprema potato cultivars in two localities with contrasting edaphoclimatic conditions.

Nutrient	Locality	Cultivar	Curve NC = a (ln (x)+b)	RMSE	CI (a) 95%	CI (b) 95%	SE a	SE b
Calcium	Chocontá	Capiro	8.33 (ln (x)-33.20)	2.86	6.43 - 10.24	(-41.89) - (-24.50)	0.96**	4.36**
		Suprema	6.18 (ln (x)-24.21)	2.94	4.22 - 8.14	(-33.14) - (-15.28)	0.98**	4.48 ns
	Facatativá	Capiro	3.81 (ln (x)-15.66)	1.05	3.05 - 4.57	(-19.13) - (-12.2)	0.38**	1.73**
		Suprema	3.55 (ln (x)-14.72)	1.55	2.43 - 4.67	(-19.84) - (-9.59)	0.56**	2.56 ns
Magnesium	Chocontá	Capiro	45.78 (ln (x)-185.1)	9.42	39.51 - 52.06	(-213.7) - (-156.4)	3.15**	14.37 ns
		Suprema	38.88 (ln (x)-157.9)	9.37	32.64 - 45.12	(-186.4) - (-129.4)	3.13**	14.28**
	Facatativá	Capiro	35.34 (ln (x)-146.9)	7.60	29.86 - 40.83	(-171.9) - (-121.8)	2.74*, **	12.52*
		Suprema	16.21 (ln (x)-67.17)	4.13	13.23 - 19.19	(-80.79) - (-53.56)	1.49*, **	6.80*, **
Sulfur	Chocontá	Capiro	58.43 (ln (x)-238.2)	10.38	51.52-65.34	(-269.8) - (-206.7)	3.46 ns	15.82 ns
		Suprema	53.78 (ln (x)-216.0)	16.88	42.54- 65.02	(-267.3) - (-164.6)	5.63**	27.73**
	Facatativá	Capiro	52.69 (ln (x)-217.8)	9.82	45.61-59.78	(-250.2) - (-185.4)	3.54*	16.17 *
		Suprema	18.0 (ln (x)-74.31)	3.73	15.30-20.69	(-86.61) - (-62.01)	1.34*, **	6.14*, **

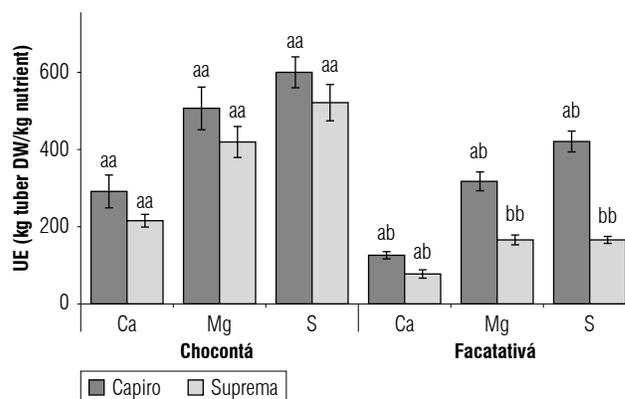
\* Significant differences between cultivars at  $P < 0.05$ . \*\* Significant differences between localities at  $P < 0.05$ . ns: No significant differences. RMSE: Root mean square error. CI: Confidence interval. SE: Standard error.



**FIGURE 4.** Translocation efficiency of Ca (CaTE) (A), Mg (MgTE) (B) and S (STE) (C) in Diacol Capiro and Pastusa Suprema potato cultivars in two localities with contrasting edaphoclimatic conditions.

### Nutrient use efficiency

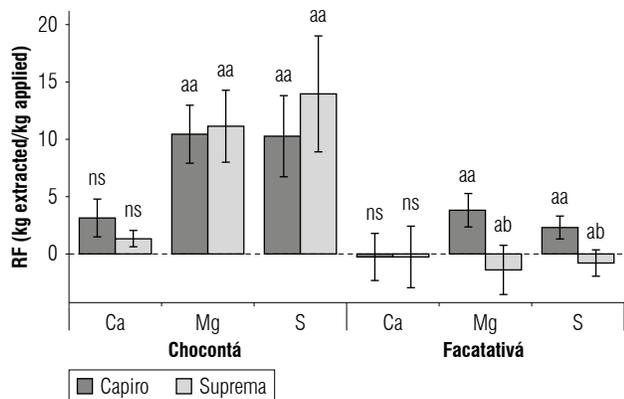
The effect of locality and cultivar were highly significant ( $P < 0.01$ ) for CaUE, MgUE and SUE, showing locality x cultivar interaction only in SUE. The use efficiency of the three nutrients was significantly higher ( $P < 0.01$ ) in Chocontá compared to Facatativá for the two cultivars (Fig. 5). For CaUE, no differences were found between cultivars in the two localities, however, in Facatativá, Capiro showed significantly ( $P < 0.05$ ) higher MgUE and SUE compared to Suprema. In Chocontá, no differences in UE were observed. Sulfur was the nutrient with the highest use efficiency with an average of 426 kg of tuber dry matter per kg of extracted nutrient, followed by Mg with 351 kg and Ca with 176 kg.



**FIGURE 5.** Ca, Mg and S use efficiency (UE) in Diacol Capiro and Pastusa Suprema potato cultivars in two localities with contrasting edaphoclimatic conditions. The first letter indicates difference between cultivars within the same locality; the second letter indicates significant differences between localities for the same cultivar. Error bars correspond to standard error.

### Nutrient acquisition or recovery efficiency

There was no effect of the locality or the cultivar on RFCa; however, RFMg and RFS did show an effect of the locality ( $P < 0.01$ ). Suprema had a significantly higher RFMg and RFS in Chocontá ( $P < 0.01$ ) compared to Facatativá (Fig. 6). No significant differences were found between cultivars. The highest recovery efficiency was found for S, followed by Mg and Ca. In Facatativá, negative values were recorded for the three nutrients.



**FIGURE 6.** Ca, Mg, and S recovery efficiency for Diacol Capiro and Pastusa Suprema potato cultivars in two localities with contrasting edaphoclimatic conditions. The first letter indicates the difference between cultivars within the same locality and the second letter indicates significant differences between localities for the same cultivar. Error bars correspond to standard error.

## Discussion

Biomass accumulation was directly related to the tuber formation as these are storage organs and constitute a high proportion of the total biomass (Ferreira *et al.*, 2019). The low translocation between 0-75 DAP is due to the fact that this stage involves the process of cellular differentiation and formation of primary stems. This stage is characterized by a low growth rate due to the limited number of storage cells, resulting in a low nutrient sink strength in the tubers (Gómez *et al.*, 2019). The greater accumulation of dry biomass between 75-100 DAP coincides with stages I and II of secondary stem formation and maximum tuberization. The faster growth observed in Suprema may be related to its indeterminate growth, and the greater accumulation of nutrients in Facatativá may be attributed to a higher cation exchange capacity (CEC) of the soil, due to its higher content of organic matter (Soriano Soto, 2020). Additionally, the higher average temperature in Facatativá may positively affect this process by accelerating metabolic processes, growth and nutrient demand; it may also be related to a higher average soil temperature (variable not monitored) that increases the intake of nutrients by the roots (Bassirirad, 2000). Although different values were found for the Ca and Mg total accumulation between the cultivars and localities, these were similar for the tuber nutrients accumulation. This suggests that the first parameter does not determine the second one. The locality did not affect the nutrient accumulation in tubers, which may be related to the fact that nutrient translocation through the phloem is mainly given by nutrient characteristics (atomic weight,

valency, ionic radius, among others) and the sink force. The absence of differences between the cultivars initially indicates that the demand or sink strength by the tuber is similar for both.

The total accumulation of Ca, Mg, and S was higher than values reported by other authors. For the Asterix variety, with yields of 62 t ha<sup>-1</sup>, Silva *et al.* (2020) reported a total accumulation of Ca of 37 kg ha<sup>-1</sup> and 2.7 kg ha<sup>-1</sup> in tubers. For the cv. MNF-80, with a yield of 36 t ha<sup>-1</sup>, Cabalceta *et al.* (2005) reported a total accumulation of 12, 10, and 11 kg ha<sup>-1</sup> of Ca, Mg, and S, respectively. For the Agatha variety, with a yield of 35 t ha<sup>-1</sup>, Soratto *et al.* (2020) reported a total Mg accumulation of 8 kg ha<sup>-1</sup> and 5 kg ha<sup>-1</sup> in tubers, which were lower than those found in the present study. The differences in nutrient accumulation compared to other research may be due to the greater yield in the present study (60-70 t ha<sup>-1</sup> in both cultivars), which increases the nutrient requirements. Likewise, the influence of genotype and experimental conditions in terms of locality, climate, soil, among others, must be considered.

The accumulation and distribution of nutrients among treatments confirm the effect of the genotype and the environment on crop growth and development (Campos & Ortiz, 2020). The higher accumulation of Ca in the aerial part is consistent with the findings of Silva *et al.* (2020), who reported a Ca partition of 93-95% in the aerial part and 5-7% in the tubers. This can be explained by the low mobility of Ca in phloem and its movement by transpiration stream (Silva *et al.*, 2020). Since the tubers have a low transpiration rate compared to the aerial parts, the accumulation of Ca in tubers is limited. These observations are consistent with that reported by different authors (Cabalceta *et al.*, 2005; Fernandes *et al.*, 2011). The greater accumulation of Ca in the tuberization stage and its low mobility highlight the importance of nutrient management that favors the availability and use of Ca by the plants from the early stages of growth. In this case, the importance of the fertilizer applications directed to the tubers is highlighted.

The total accumulation of Mg and tuber Mg was higher than that reported by Silva *et al.* (2020) for four potato varieties. However, the results were in line with the accumulation pattern proposed by the authors, in which the accumulation of Mg in the aerial part increased as the development of the crop advanced, but when tuberization began, Mg accumulation was mainly in the tubers. The decrease in Mg accumulation in the tubers towards the end of the cycle (maximum tuber maturation) may be

attributed to a lower Mg requirement due to the reduction in the transport of photoassimilates, where Mg acts as an allosteric activator of ATPases (Koch *et al.*, 2020). The lower production of proteins may be linked to the decrease in the tuber content of Mg and S at the end of the cycle, as Mg participates in the synthesis of amino acids, and sulfur is a structural part of amino acids such as methionine and cysteine (Koch *et al.*, 2020; Wszelaczyńska *et al.*, 2020).

The highest TE of nutrients to the tuber coincided with the tuberization and tuber filling stages, stages in which translocation of photoassimilates, cell wall formation and protein synthesis are required (Naumann *et al.*, 2020). Capiro was the genotype with greater sink force and was more efficient in the translocation of nutrients to the tubers, regardless of the locality. In contrast, Suprema showed better performance under the edaphoclimatic conditions of Chocontá (soils of low fertility and higher altitude). The differential behavior of cultivars in the Chocontá locality corroborates that, even though both belong to the Andigenum Group, there are genotypic differences that influence their performance in this locality. These results agree with what was previously reported for nutrients K and P by Gómez *et al.* (2019).

Calcium was the element with the greatest variation in TE between localities. This is related to the mean differential temperature between both. Since Ca moves by the transpiration current, the higher evapotranspiration in Chocontá could have favored its translocation. This variable is influenced by the direct accumulation of Ca in the tubers through the roots that develop on tubers and stolons (Koch *et al.*, 2020; Palta, 2010). The low average translocation of Ca was related to the fact that Ca is used mainly as a structural component of cell walls and membranes and has low mobility to the tubers. On the other hand, the higher values of Mg and S are due to their requirement for the translocation of photoassimilates, protein formation, and the regulation of cation-anion transport (Campos & Ortiz, 2020; Koch *et al.*, 2020). The translocation of Ca in both cultivars could indicate similar requirements that could be seen in homogeneous characteristics such as postharvest quality and resistance to mechanical damage; however, this must be confirmed with future research. Likewise, it is of interest to establish in future studies whether Capiro's higher Mg and S translocation is reflected in higher protein and starch contents.

The UE values in Chocontá were higher because the production of tubers (dry weight) generally was higher and resulted

from a significantly lower total accumulation of nutrients. This may be related to the greater evapotranspiration in Chocontá, which favors the accumulation and partitioning of nutrients and photoassimilates. On the other hand, Capiro proved to be the cultivar with the highest nutrient efficiency in both localities. These results should not be confused with the performance in total production, where Suprema in Chocontá had the highest production in terms of dry weight (Gómez *et al.*, 2018), while, in Facatativá, it was Capiro. It is of interest for future research to investigate why, in Facatativá, the difference was significant only for Mg and S. In recent years, research has increased on the intake of nutrients; however, studies on internal nutrient use efficiency are scarce (Tamagno *et al.*, 2017).

RF must be interpreted according to three conditions or scenarios that can occur separately or together: amount of nutrient that is taken up based (1) on the plant requirements, (2) on plant capacity (plant-roots), or (3) on plant possibility (external soil-climate conditions). Even though in the Chocontá locality the fertilization dose was higher, the RF of the three nutrients was higher than in Facatativá. This shows the greater need due to the condition of low soil fertility at the locality (more acidic pH, lower CEC and nutrient content). The higher RF in Chocontá is not considered as a response to a better root development since, even though the root weight was not recorded, the amount of the plant-absorbed nutrients was higher in Facatativá. Negative or low RF values in Facatativá should be understood as low or no need for the nutrient supply since the nutrients supplied were not used, possibly due to an excess of application or an imbalance between nutrients. To establish the effect of soil characteristics on RF, it is necessary in the future to establish the amount of nutrient that is lost by leaching or immobilization. It should be noted that the RF of Ca, Mg and S is lower (<15%) compared to that reported in previous publications for the macronutrients N and K (> 40%) (Gómez *et al.*, 2018), due to their easy loss in the soil by leaching or by immobilization (Senbayram *et al.*, 2015; White & Broadley, 2003). Ramaekers *et al.* (2010) suggest that to increase the RF, it is crucial to promote greater roots development, better hierarchical distribution of roots and a greater production of absorbent hairs, which would favor nutrient uptake. Additionally, a greater availability of nutrients in the soil must be ensured, considering its composition, incompatibility, and imbalance between nutrients, among others. Finally, the effect of continuous cultivation cycles on the properties of the soil and on its fertility should be considered, as over time these can affect RF (Duarte *et al.*, 2019; Stewart, 2007).

## Conclusions

The cultivars Diacol Capiro and Pastusa Suprema show different accumulation and translocation processes for Ca, Mg, and S, which depend on the genotype x environment interaction. Capiro shows greater adaptation to the climate and soil conditions of Facatativá, while Suprema performs better in Chocontá. Nutrient requirements follow the order of  $Ca > Mg > S$ , while translocation follows  $S > Mg > Ca$ . A more in-depth analysis of the nutrition physiology of these nutrients reveals that even when accumulation was favored by Facatativá conditions, the use, recovery and translocation efficiencies of nutrients were higher in Chocontá, positively impacting plant performance in this locality. The model curves for accumulation, as well as translocation, use and recovery efficiencies of Ca, Mg and S were established and can be used as a tool to adjust Ca, Mg, and S fertilizer doses based on crop nutrient requirements.

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## Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

## Author contributions

KC: Methodology, visualization, and writing — original draft; MIG: conceptualization, funding acquisition, and research; LER: supervision, validation. All authors reviewed and approved the final version of the manuscript.

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