

DRY MATTER AND NUTRIENT ACCUMULATION CURVE IN CABBAGE CROP¹

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ABSTRACT – Cabbage cultivars currently cultivated present high yield potential and may present differences regarding absorption and use of nutrients. Thus, studies quantifying plant growth and nutrient accumulation are the basis to improve fertilization efficiency and optimize yield. This study aimed to determine the dry matter and nutrient (N, P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn) accumulation curve of cabbage cultivars during two growing seasons. Cultivars Astrus Plus and Green Valley were cultivated during summer-autumn crop season, while Astrus Plus and Fênix during the autumn-winter crop season. Plants were sampled after transplanting at 10-day intervals until harvest. Dry matter and nutrient accumulations are variable with growing season and cultivar. The highest dry matter and nutrient accumulation rates occur in the last ten days of the cycle. Fertilizations with N, P, K, Fe, and Zn should receive more attention due to higher harvest indices.

Keywords: *Brassica oleracea* var. *capitata*. Nutrient extraction. Harvest index.

CURVA DE ACÚMULO DE MATÉRIA SECA E DE NUTRIENTES PELA CULTURA DO REPOLHO

RESUMO – As cultivares de repolho utilizadas atualmente têm alto potencial produtivo e podem apresentar diferenças na absorção e utilização de nutrientes. Dessa forma, pesquisas com a quantificação do crescimento das plantas e da acumulação de nutrientes são básicas para melhorar a eficiência de fertilização do solo e otimizar a produção. Objetivou-se, com este trabalho, determinar as curvas de acúmulo de matéria seca (MS) e de nutrientes (N, P, K, Ca, Mg, S, Cu, Fe, Mn e Zn) por cultivares de repolho em duas épocas de cultivo. No verão-outono foram utilizadas as cultivares ‘Astrus Plus’ e ‘Green Valley’, e no outono-inverno, ‘Astrus Plus’ e ‘Fênix’. As plantas foram amostradas, após o transplante, em intervalos de 10 dias até a colheita. O acúmulo de matéria seca e de nutrientes é variável com a época de cultivo e com a cultivar. As maiores taxas de acúmulo de matéria seca e de nutrientes ocorrem nos 10 últimos dias do ciclo. As adubações com N, P, K, Fe e Zn devem receber maior atenção em razão de apresentarem os maiores índices de colheita.

Palavras-chave: *Brassica oleracea* var. *capitata*. Extração de nutrientes. Índice de colheita.

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INTRODUCTION

Recommendations for soil fertility correction and fertilization of cabbage crop are scarce (CECÍLIO FILHO; SILVA; CORTEZ, 2013). Therefore, recommended fertilizer doses usually underestimate the nutrient demand related to high yield and commercial standards of modern cabbage cultivars (AQUINO et al., 2005).

There is a disagreement between fertilizer applications recommended in the literature and those effectively applied by farmers, who usually apply higher nutrient doses. Thus, the current fertilization management does not provide nutrients in balance with crop requirements, which results in waste of fertilizers and low recovery efficiency (ZHANG et al., 2010). Furthermore, brassicas show differences in accumulation as a function of growing seasons and genotypic variability (KOPSELL et al., 2005).

Because of the short cycle of most vegetable crops, nutrient demand is concentrated in the short term. It makes important the knowledge of nutrient absorption and accumulation characteristics at different development stages (CASTOLDI et al., 2009). For this, nutrient accumulation curves should be determined in order to know the time when nutrients are most required, plan more rational cultivation methods, and optimize the recommended dose and time of fertilizer application (BENDER; HAEGELE; BELOW, 2015).

Absorption curves include the nutrient ratio in commercial organs (heads, in the case of cabbage) regarding the total accumulation. This ratio, also known as harvest index, is important for nutrient flow in the soil. The nutrients most accumulated in the commercial organ can lead to soil impoverishment, especially when fertilizations are lower when compared to the exported quantities and

nutrient is required in large quantities (AQUINO et al., 2015). Therefore, studies on quantification of plant growth and nutrient accumulation are the basis to improve soil fertility efficiency, optimize yield, and reduce the environmental impact caused by excess fertilizers (CORTEZ et al., 2013).

However, nutrient absorption curve indicates plant need and not the dose to be applied, which varies according to the nutrient recovery efficiency by the crop, which in turn varies as a function of soil type, weather conditions, crop management, and source (CASTOLDI et al., 2009).

Cabbage cultivars currently cultivated have high yield potential and may differ regarding nutrient absorption and use, which leads to the need for determining the nutrient requirement of different cultivars in the growing regions. Thus, this study aimed to determine dry matter (DM) and nutrient (N, P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn) accumulation curve of cabbage cultivars.

MATERIAL AND METHODS

Nutrient accumulation curves were determined in two growing seasons, the first during summer-autumn and the second during autumn-winter in two commercial fields of cabbage cultivation in São Gotardo, MG. The areas were at an altitude of 1,100 m and a prevailing Cwa climate according to Köppen-Geiger classification (PEEL; FINLAYSON; McMAHON, 2007). Weather data recorded during the experiment are shown in Figure 1. Soils of both areas are classified as Haplustox (Red Yellow Latosol with a very clayey texture, according to the Brazilian Soil Classification System), whose chemical attributes are shown in Table 1.

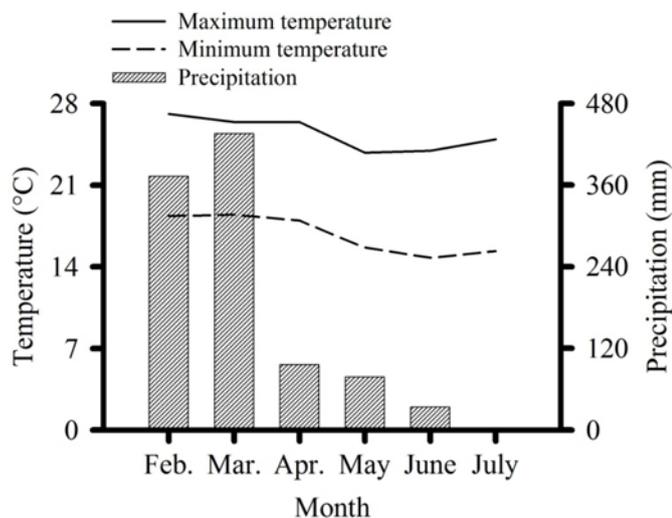


Figure 1. Maximum and minimum temperatures and precipitation during the experimental period. Alto Paranaíba region, MG (2015).

Table 1. Soil chemical analyses of the experimental areas at a depth at 0–20 cm.

Chemical attribute	Unit	Extractor/Method	Growing season	
			Summer-autumn	Autumn-winter
pH	–	CaCl ₂	5.6	5.9
P-rem	mg L ⁻¹	CaCl ₂	13.4	7.4
P	mg dm ⁻³	Mehlich-1	33.3	24.3
K	mg dm ⁻³	Mehlich-1	86.0	97.8
Ca	cmol _c dm ⁻³	KCl	3.9	4.9
Mg	cmol _c dm ⁻³	KCl	1.0	1.5
S	mg dm ⁻³	Calcium phosphate	10.0	17.0
B	mg dm ⁻³	Hot water	1.5	1.1
Cu	mg dm ⁻³	DTPA	2.6	2.3
Fe	mg dm ⁻³	DTPA	26.0	52
Mn	mg dm ⁻³	DTPA	1.5	3.2
Zn	mg dm ⁻³	DTPA	7.5	6.7
Al	cmol _c dm ⁻³	KCl	0.0	0.0
H+Al	cmol _c dm ⁻³	SMP buffer solution	3.1	2.6
Organic matter	g dm ⁻³	–	38.0	29.0
Sum of bases	cmol _c dm ⁻³	–	5.1	6.7
Cation exchange capacity	cmol _c dm ⁻³	–	8.3	9.3
Base saturation	%	–	62.0	71.7

P and K – Mehlich-1; Ca, Mg, and Al – 1 mol L⁻¹ KCl; S–SO₄ – 0.01 mol L⁻¹ monobasic calcium phosphate; B – hot water; Cu, Fe, Mn, and Zn – DTPA at pH 7.3; H+Al – SMP buffer solution at pH 7.5; Organic matter – Walkley-Black.

Soil tillage consisted of a subsoiling, harrowing, and rotary hoeing, with pits spaced at 0.35 × 0.38 m, resulting in a population of 75.188 plants ha⁻¹. In the summer-autumn, nitrogen, phosphorus, and potassium fertilization consisted of 150 kg ha⁻¹ of N, 850 kg ha⁻¹ of P₂O₅, and 160 kg ha⁻¹ of K₂O, respectively. In the autumn-winter, 210 kg ha⁻¹ of N, 700 kg ha⁻¹ of P₂O₅, and 320 kg ha⁻¹ of K₂O were applied. All fertilizers were broadcast applied and incorporated at planting, including phosphate fertilizers, as adopted by farmers in the Alto Paranaíba region, MG.

In the summer-autumn, seedlings of the cultivars Astrus Plus and Green Valley were transplanted to the field on February 13, 2015, and harvested on April 23, 2015. The cultivar Astrus Plus has good compactness, good market acceptance, and medium to large sized heads, with slightly flattened shape and weight ranging from 1.4 to 2.2 kg. It is the cultivar most used by farmers in the Alto Paranaíba region, MG, as it can be cultivated throughout the year. The cultivar Green Valley presents vigorous foliage and medium-sized heads, with flattened globular shape and weight ranging from 2.0 to 2.5 kg.

In the autumn-winter, seedlings of the cultivars Astrus Plus and Fênix were transplanted to

the cultivation area on May 1, 2015, and harvested on July 10 and 20, 2015, respectively. The cultivar Fênix presents medium semi-flattened heads and mean weight from 2.5 to 3.0 kg, with the preferential growing season in the winter.

All cultivars had seedlings produced in 200-cell trays under a protected environment and using an agricultural substrate based on coconut fiber and vermiculite, with transplanting at 35 days after sowing.

Weed management was carried out with a pre-planting application of oxyfluorfen (2-chloro- α,α,α -trifluoro-p-tolyl 3-ethoxy-4-nitrophenyl ether) and manual weeding over the cycle when necessary. Phytosanitary management of the experiments followed the procedure adopted in the commercial area, in which decision-making was based on pest and disease monitoring. The crop was irrigated by a central pivot when necessary, with a water depth calculated from the data collected in weather stations installed near the experiments.

Plants were sampled after transplanting at 10-day intervals until harvest. Twelve plants (four replications with three plants each) were sampled at each collection time by cutting them close to the soil surface. Cabbage crop was harvested when plants presented well-formed heads and compactness

required for commercialization, which occurred at 70 days after transplanting (DAT) in the summer-autumn season and 70 and 80 DAT for the cultivars Fênix and Astrus Plus, respectively, in the autumn-winter season. Plants were divided into commercial (head) and non-commercial parts (outer leaves + stem) at that time.

After each sampling, samples were washed to remove impurities and dried in a forced air circulation oven at 70 °C for 72 h. Subsequently, these samples were ground in a Wiley mill fitted with a 1.27-mm sieve to determine nutrient contents (N, P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn), according to Malavolta, Vitti, and Oliveira (1997).

The data were analyzed by descriptive statistics. Curves and equations of DM and nutrient accumulation were adjusted using the software Sigma Plot v. 10.0. Harvest indices were given by the percentage of DM and nutrients accumulated in the heads in relation to their total amount accumulated in the whole plant.

RESULTS AND DISCUSSION

Accumulation curve, export, and harvest index of DM and macronutrients

Two distinct phases were observed for DM accumulation (Figure 2). The first phase (up to 30 DAT) comprised the initial period of crop development, in which the growth rates were lower for the cultivars Astrus Plus and Green Valley in the summer-autumn, with values of 27.9 and 31.4 kg ha⁻¹ day⁻¹, respectively, when compared to the cultivars Astrus Plus and Fênix in the autumn-winter, with values of 41.2 and 42.0 kg ha⁻¹ day⁻¹, respectively. It can be attributed to the stress caused by the transplanting or slow initial growth that is characteristic of crucifers. This result was also verified by Übelhör, Gruber, and Claupein (2014) in white cabbage and Castoldi et al. (2009) and Gondim et al. (2011), who observed around 17 and 20% of the total accumulation, respectively, up to 30 DAT in cauliflower.

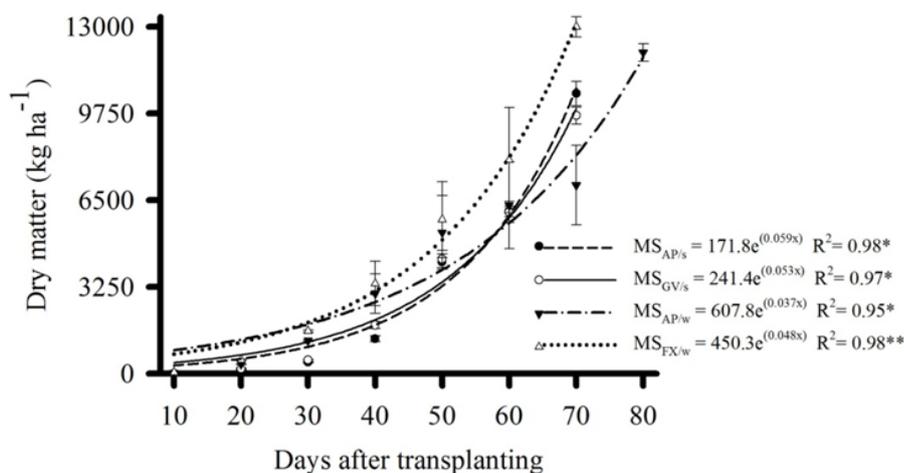


Figure 2. Dry matter accumulation curve for the cultivars Astrus Plus (AP/s) and Green Valley (GV/s) in the summer-autumn and Astrus Plus (AP/w) and Fênix (FX/w) in the autumn-winter.

**and *are significant at 1 and 5%, respectively, by the t-test.

The second phase started at approximately 30 DAT (Figure 2). There was a higher shoot growth, which was more pronounced in the last ten days of the cycle for all cultivars. The highest DM accumulation rates were observed during this period, with values of 476.1 kg ha⁻¹ day⁻¹ in the summer-autumn and 362.7 kg ha⁻¹ day⁻¹ in the autumn-winter for the cultivar Astrus Plus, and 387.7 and 494.2 kg ha⁻¹ day⁻¹ for the cultivars Green Valley and Fênix, respectively.

Comparatively, from 60 to 70 DAT, for the cultivar Astrus Plus in the autumn-winter, and 50 to 60 DAT, for the other cultivars, the accumulation rates were 263.9, 238.8, 250.6, and 305.8 kg ha⁻¹ day⁻¹ for the cultivars Astrus Plus in the summer-autumn, Green Valley and Astrus Plus in autumn-winter, and Fênix. The highest DM accumulation rate during this period may be related to an intense

cell division during the final stage of head formation.

Shoot DM production was higher at harvest, with values of 9,673 to 10,499 kg ha⁻¹ in the summer-autumn and 12,043 to 12,995 kg ha⁻¹ in the autumn-winter (Table 2). These values are higher when compared to those found by Aquino et al. (2009) (8,308 kg ha⁻¹) and Correa, Cardoso, and Claudio (2013) (6,156 and 3,563 kg ha⁻¹), which may be attributed to the use of different hybrids. However, Cecílio Filho et al. (2011) found 6,438 kg ha⁻¹ for the cultivar Astrus Plus, which may be related to the lower plant population used. Moreover, the higher DM production of the present study may also be attributed to higher yields, with values of 124.5, 152.3, 106.7, and 142.8 t ha⁻¹ for the cultivar Astrus Plus in summer-autumn and autumn-winter, Green Valley and Fênix, respectively.

Table 2. Amount of dry matter and macronutrients accumulated[†] in cabbage heads and outer leaves and harvest index for the cultivars Astrus Plus and Green Valley in the summer-autumn growing season and Astrus Plus and Fênix in the autumn-winter growing season.

Variable	Accumulation (kg ha ⁻¹)		Harvest index (%)	Accumulation (kg ha ⁻¹)		Harvest index (%)
	Heads	Outer leaves		Heads	Outer leaves	
Summer-autumn						
	Astrus Plus			Green Valley		
Dry matter	7,620 ± 490.8	2,879 ± 230.9	72 ± 2.1	6,528 ± 273.2	3,145 ± 145.3	68 ± 1.3
N	254 ± 8.3	79 ± 5.9	76 ± 1.7	188 ± 7.2	84 ± 4.6	69 ± 1.5
P	65 ± 5.9	14 ± 1.7	82 ± 1.1	42 ± 4.5	15 ± 1.0	74 ± 1.1
K	419 ± 50.7	210 ± 25.9	67 ± 3.9	356 ± 27.6	170 ± 5.8	68 ± 1.9
Ca	72 ± 6.4	234 ± 65.2	24 ± 4.4	350 ± 15.8	290 ± 3.0	55 ± 1.1
Mg	21 ± 1.8	20 ± 7.4	52 ± 7.8	60 ± 2.1	34 ± 0.6	63 ± 0.9
S	47 ± 2.5	45 ± 1.4	51 ± 1.4	38 ± 1.6	44 ± 5.2	46 ± 3.5
Autumn-winter						
	Astrus Plus			Fênix		
Dry matter	9,024 ± 148.7	3,020 ± 270.9	73 ± 1.5	9,031 ± 216.8	3,964 ± 280.6	68 ± 1.4
N	223 ± 4.7	70 ± 1.5	76 ± 0.7	241 ± 4.0	104 ± 2.5	70 ± 0.8
P	49 ± 1.4	12 ± 0.6	80 ± 0.7	51 ± 2.3	16 ± 0.9	76 ± 1.2
K	335 ± 13.4	131 ± 1.4	72 ± 1.0	367 ± 27.2	161 ± 15.4	70 ± 2.9
Ca	48 ± 3.2	115 ± 8.8	30 ± 1.4	49 ± 3.2	157 ± 17.9	24 ± 1.7
Mg	17 ± 0.6	15 ± 0.7	54 ± 1.1	23 ± 0.3	28 ± 1.3	45 ± 1.1
S	39 ± 0.9	29 ± 2.1	57 ± 2.2	46 ± 2.3	39 ± 3.6	54 ± 3.1

[†]Mean ± standard deviation.

Yields were higher in the autumn-winter growing season than those found in the summer-autumn, which may be related to the occurrence of milder temperatures (Figure 1), which allow a higher brassica growth. According to Rahman, Hadley, and Pearson (2007), the optimal temperature range for cauliflower after curd initiation is 19 to 23 °C. Kalisz et al. (2012) verified a higher yield in Chinese cabbage (*B. rapa* var. *chinensis*) under mean temperatures from 16.7 to 20.0 °C.

A little difference was observed between cultivars and growing seasons for the harvest index of DM (Table 2). The harvest indices ranged from 67 to 73% in the summer-autumn and 69 to 75% in the autumn-winter. These values are higher when compared to those found by Cecílio Filho et al. (2011) for the cultivar Astrus Plus (57%) and Correa, Cardoso, and Claudio (2013) for the cultivar Kenzan (47 and 49%), which may be due to the higher yield obtained in the present study and the highest plant population.

Regarding macronutrient accumulation, N accumulation curves were similar to that of DM accumulation only in the summer-autumn (Figure 3a). The highest accumulation rate at this growing season was observed from 60 to 70 DAT, with a value of 14.2 kg N ha⁻¹ day⁻¹ for the cultivar Astrus Plus and 10.5 kg N ha⁻¹ day⁻¹ for Green Valley. The accumulation rates were constant in the autumn-winter, with values of 4.3 and 5.8 kg N ha⁻¹ day⁻¹ for the cultivar Astrus Plus and Fênix, respectively.

Phosphorus accumulation curves were also

similar to that of DM accumulation (Figure 3b). The highest P accumulation rates were observed in the last ten days of the cycle for all cultivars and growing seasons. The values found in the summer-autumn were 3.8 and 2.7 kg P ha⁻¹ day⁻¹ for the cultivars Astrus Plus and Green Valley, respectively, and 1.8 and 2.4 kg P ha⁻¹ day⁻¹ for Astrus Plus and Fênix, respectively, in the autumn-winter.

Potassium accumulation rate was continuous over the cycle for all cultivars and growing seasons (Figure 3c). The observed K contents were 10.7 and 8.8 kg ha⁻¹ day⁻¹ for the cultivars Astrus Plus and Green Valley in the summer-autumn growing season, respectively, and 6.8 and 5.8 kg ha⁻¹ day⁻¹ for Astrus Plus and Green Valley in the autumn-winter, respectively.

Calcium accumulation curves were different according to the growing seasons (Figure 3d). They were similar to the DM accumulation curve in the summer-autumn, but presented a decrease in the accumulation rate after 40 and 50 DAT for the cultivars Astrus Plus and Fênix, respectively, in the autumn-winter. The highest accumulation rates were found between 60 and 70 DAT in the summer-autumn, with a value of 13.5 kg Ca ha⁻¹ day⁻¹ for Astrus Plus and 17.7 kg Ca ha⁻¹ day⁻¹ for Green Valley. However, the highest accumulation rates in the autumn-winter were observed from 30 to 40 DAT for the cultivar Astrus Plus (5.6 kg Ca ha⁻¹ day⁻¹) and 40 to 50 DAT for the cultivar Fênix (5.9 kg Ca ha⁻¹ day⁻¹).

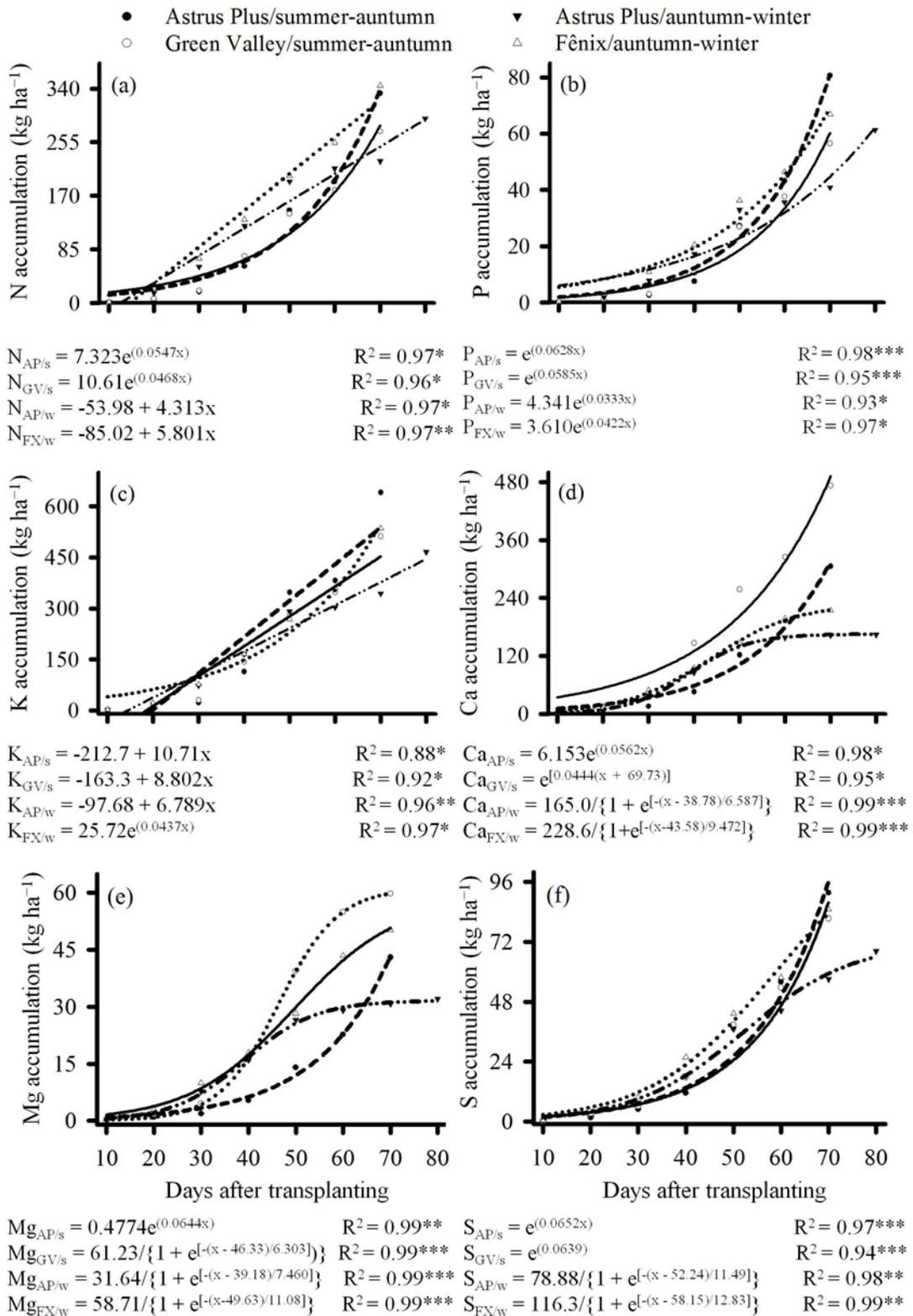


Figure 3. Nitrogen (a), phosphorus (b), potassium (c), calcium (d), magnesium (e), and sulfur (f) accumulation curves for the cultivars Astrus Plus (AP/s) and Green Valley (GV/s) in the summer-autumn and Astrus Plus (AP/w) and Fênix (FX/w) in the autumn-winter.

***, **, and * are significant at 0.1, 1, and 5%, respectively, by the t-test.

The Mg accumulation curve presented a similar behavior to that of DM for the cultivar Astrus Plus in the summer-autumn season, while the accumulation rate decreased from 40 DAT in the autumn-winter, which was also observed for the cultivars Green Valley and Fênix after 50 DAT (Figure 3e). Therefore, the period with the highest Mg accumulation rate was different between cultivars and growing seasons. Astrus Plus presented the highest accumulation rate, with values of 2.1 kg Mg ha⁻¹ day⁻¹ from 60 to 70 DAT in the summer-autumn and 1.0 kg Mg ha⁻¹ day⁻¹ from 30 to 40 DAT in the autumn-winter. The highest accumulation rates were found from 40 to 50 DAT for the cultivars Green Valley and Fênix, with values of 2.3 and 1.3 kg ha⁻¹ day⁻¹, respectively.

Sulfur accumulation curves were similar to the respective DM accumulation curves in the summer-autumn (Figure 3f). Thus, the highest accumulation rate was observed in the last ten days of the cycle for the cultivars Astrus Plus and Green Valley, with values of 4.6 and 4.1 kg S ha⁻¹ day⁻¹, respectively. In the autumn-winter, sulfur accumulation increased up to 60 DAT for both cultivars, with the highest rates observed from 50 to 60 DAT, with values of 1.7 kg S ha⁻¹ day⁻¹ for Astrus Plus and 2.2 kg S ha⁻¹ day⁻¹ for Fênix.

In general, a higher nutrient accumulation was observed close to cabbage harvest time, unlike cauliflower, in which all macronutrients are accumulated in the middle third of the crop cycle (CASTOLDI et al., 2009; TAKEISHI; CECÍLIO FILHO; OLIVEIRA, 2009). Takeishi, Cecílio Filho, and Oliveira (2009) attributed the increased nutrient accumulation in cauliflower in the middle third of its cycle to the increased number of leaves, leaf area, and DM during this period. This pattern is different in cabbage (Figure 2) most likely because its absorption curve was determined before inflorescence emission and during a period of full vegetative growth.

The amount of macronutrients accumulated in the heads (export) of the cultivar Astrus Plus was higher in the summer-autumn when compared to the autumn-winter for all nutrients (Table 2). This result agrees with Citak and Sonmez (2010), who found higher P, K, and Mg contents in cabbage heads cultivated under higher temperature.

The most exported macronutrient for all cultivars was K (Table 2). The exported K content for the cultivar Astrus Plus was higher in the summer-autumn when compared to the autumn-winter growing season, with values of 419 and 335 kg K ha⁻¹, respectively. These contents were similar for the other cultivars, i.e., 343 kg K ha⁻¹ for Green Valley and 367 kg ha⁻¹ for Fênix. These values exceed those found by Aquino et al. (2009) and Correa, Cardoso, and Claudio (2013), who observed values of 295 and 197 kg K ha⁻¹, respectively. The highest extractions obtained in this study can be

attributed to a higher DM production because the applied doses and soil K contents were similar to those of the cited studies. A significant and positive effect was observed for plant population on K export (AQUINO et al., 2009), which may explain the high quantity of exported K since the population was higher when compared to those used in other studies.

Potassium was the most accumulated nutrient by cabbage, which was also observed by Correa, Cardoso, and Claudio (2013), who found that only planting fertilization with 240 kg K₂O ha⁻¹ was enough to reach the maximum yield, without significant differences from the K topdressing fertilization. However, as observed in this study, K is continuously demanded by the crop throughout the cycle (Figure 3c). Because K has a susceptibility to leaching in sandy soils and under high-intensity precipitation, applying its full dose at planting cannot be a good agricultural practice. Moreover, considering the extraction values (Table 2) and yield obtained in the present study, the dose of 240 kg K₂O ha⁻¹ is not enough to supply the demand of the cultivars. Higher doses to be applied suggest the need for splitting the fertilization for a better recovery efficiency.

Nitrogen was the second most exported macronutrient by all cultivars. The cultivar Astrus Plus also presented a higher export in the summer-autumn when compared to autumn-winter, with values of 254 and 223 kg N ha⁻¹, respectively (Table 2). Also, export reached values of 188 kg N ha⁻¹ for the cultivar Green Valley and 241 kg N ha⁻¹ for the cultivar Fênix (Table 2). These N contents were below that found by Aquino et al. (2009) (279 kg ha⁻¹), which could be explained by the higher N content, as they found a linear response between N content and the applied N, which was estimated by applying 300 kg N ha⁻¹. These results corroborate Sturm et al. (2010), who observed an accumulation of 246 kg N ha⁻¹ by applying 200 kg N ha⁻¹ in white cabbage, and Yun and Ro (2009), who verified a linear response of N accumulation with N doses.

A difference was observed between growing seasons for the third most exported nutrient, which was Ca in the summer-autumn and P in the autumn-winter (Table 2). The cultivar Astrus Plus exported 72 kg Ca ha⁻¹, and the Green Valley exported 182 kg Ca ha⁻¹ in the summer-autumn. Similar export values were observed among cultivars in the autumn-winter, with values of 48 and 49 kg Ca ha⁻¹ for Astrus Plus and Fênix, respectively. Therefore, the amount of Ca exported by the cultivar Green Valley was higher when compared to that observed in the other cultivars, which is different from the range of values found in the literature. Aquino et al. (2009) observed an export of 88 kg Ca ha⁻¹, while Correa, Cardoso, and Claudio (2013) reported extraction of 35 kg Ca ha⁻¹, both studies using the hybrid Kenzan and similar soil Ca contents.

Although yield was lower in the summer-

autumn in comparison with the autumn-winter, the cultivar Astrus Plus showed higher P export (Table 2). It may be related to the higher P content in the soil and the highest dose used in the summer-autumn growing season (33.3 mg dm⁻³ and 850 kg P₂O₅ ha⁻¹, respectively), which allowed a higher accumulation by plants. Cabbage can mobilize and absorb P from the soil by additional mechanisms, such as exudation of the organic acid citrate, which increases P recovery efficiency (DECHASSA; SCHENK, 2004). P export was similar in the cultivars Green Valley and Fênix, with values of 42 and 51 kg P ha⁻¹, respectively. In soil with high P availability (P_{resin} = 93.0 mg dm⁻³), Cecilio Filho, Silva, and Cortez (2013) found 16 kg P ha⁻¹ as the maximum export by applying 360 kg P₂O₅ ha⁻¹, which is lower than the values found in the present study. This observation may be related to the hybrid Fuyutoyo used and yield obtained by the authors (69.6 t ha⁻¹). This difference caused by hybrids and yield can also explain the export higher than 28 kg P ha⁻¹, as observed by Aquino et al. (2009).

The amount of S exported by the cultivar Astrus Plus in the summer-autumn was similar to that of Fênix, with 47 and 46 kg ha⁻¹, respectively (Table 2). The similarity was also observed between the export values of the cultivars Green Valley and Astrus Plus in the autumn-winter, with 38 and 39 kg ha⁻¹, respectively. However, all cultivars presented export lower than the 50 kg S ha⁻¹ found by Aquino et al. (2009), which may be related to the lower S availability in the soils of the present study.

Magnesium was the last macronutrient in order of export and the cultivar Astrus Plus exported less when compared to the other cultivars, regardless of the growing season (Table 2). This cultivar exported 21 kg ha⁻¹ in the summer-autumn and 17 kg ha⁻¹ in autumn-winter. The cultivar Green Valley exported 26 kg ha⁻¹ and Fênix exported 23 kg ha⁻¹. These exports were higher when compared to those observed by Correa, Cardoso, and Claudio (2013), which is probably due to the higher DM production of the present study.

The nutrients N, P, and K presented the highest harvest indices and, in general, the cultivar Astrus Plus had higher harvest indices than other cultivars (Table 2). The harvest indices varied from 74 to 82% for P, 69 to 76% for N, and 65 to 72% for K. Thus, greater attention should be given to the replacement of these nutrients in order to avoid soil impoverishment (BENDER; HAEGELE; BELOW, 2015), as they are absorbed in high amounts and have a larger partition for leaves that comprise the head, resulting in the high export rate.

Accumulation curve, export, and harvest index of micronutrients

All cultivars, except Fênix, presented practically constant Cu accumulation rates up to the last ten days of the cycle when a considerable increase in this rate was observed (Figure 4a). Thus, the accumulation rates during this period were 4.0, 9.7, and 4.3 g Cu ha⁻¹ day⁻¹ for the cultivars Astrus Plus in summer-autumn and autumn-winter and Green Valley, respectively. The highest accumulation rate for the cultivar Fênix occurred from 40 to 50 DAT, with a value of 29.8 g Cu ha⁻¹ day⁻¹, which is considered high and probably due to the contamination by foliar sprayings with cupric fungicides.

Iron accumulation rate decreased at 50 DAT for the cultivars Green Valley and Astrus Plus in the autumn-winter and 60 DAT for the cultivar Fênix (Figure 4b). Thus, the highest accumulation rate was verified from 40 to 50 DAT, with values of 109.7 and 21.5 g Fe ha⁻¹ day⁻¹ for Green Valley and Astrus Plus in the autumn-winter, respectively. Also, the highest accumulation rate occurred from 50 to 60 DAT for the cultivar Fênix, with a value of 45.6 g Fe ha⁻¹. The cultivar Astrus Plus showed a distinct behavior in the summer-autumn in relation to the other cultivars, with increasing Fe accumulation over the cycle, especially in the last ten days of the cycle, in which the accumulation rate was 125.9 g Fe ha⁻¹ day⁻¹.

Manganese accumulation curves practically followed DM accumulation curves, with the highest accumulation rates observed in the last ten days of the cycle for all cultivars (Figure 4c). Thus, 14.5 and 16.4 g Mn ha⁻¹ day⁻¹ were found in the summer-autumn for the cultivars Astrus Plus and Green Valley, respectively, and 7.9 and 39.8 g Mn ha⁻¹ day⁻¹ in the autumn-winter for Astrus Plus and Fênix, respectively.

Finally, the highest Zn accumulation rates also occurred in the last ten days of the cycle for all cultivars (Figure 4d). The accumulation rates obtained in the autumn-winter were 39.4 and 8.4 g Zn ha⁻¹ day⁻¹ for the cultivars Astrus Plus and Green Valley, respectively. On the other hand, the rates in the autumn-winter were 8.0 and 11.5 g Zn ha⁻¹ day⁻¹ for Astrus Plus and Fênix, respectively.

As observed for macronutrients, the highest micronutrient accumulation rate in cabbage occurred in the last 10 days of the cycle, which is different from cauliflower, in which the highest accumulation occurred in the middle third of the crop cycle (CASTOLDI et al., 2009; TAKEISHI; CECÍLIO FILHO; OLIVEIRA, 2009).

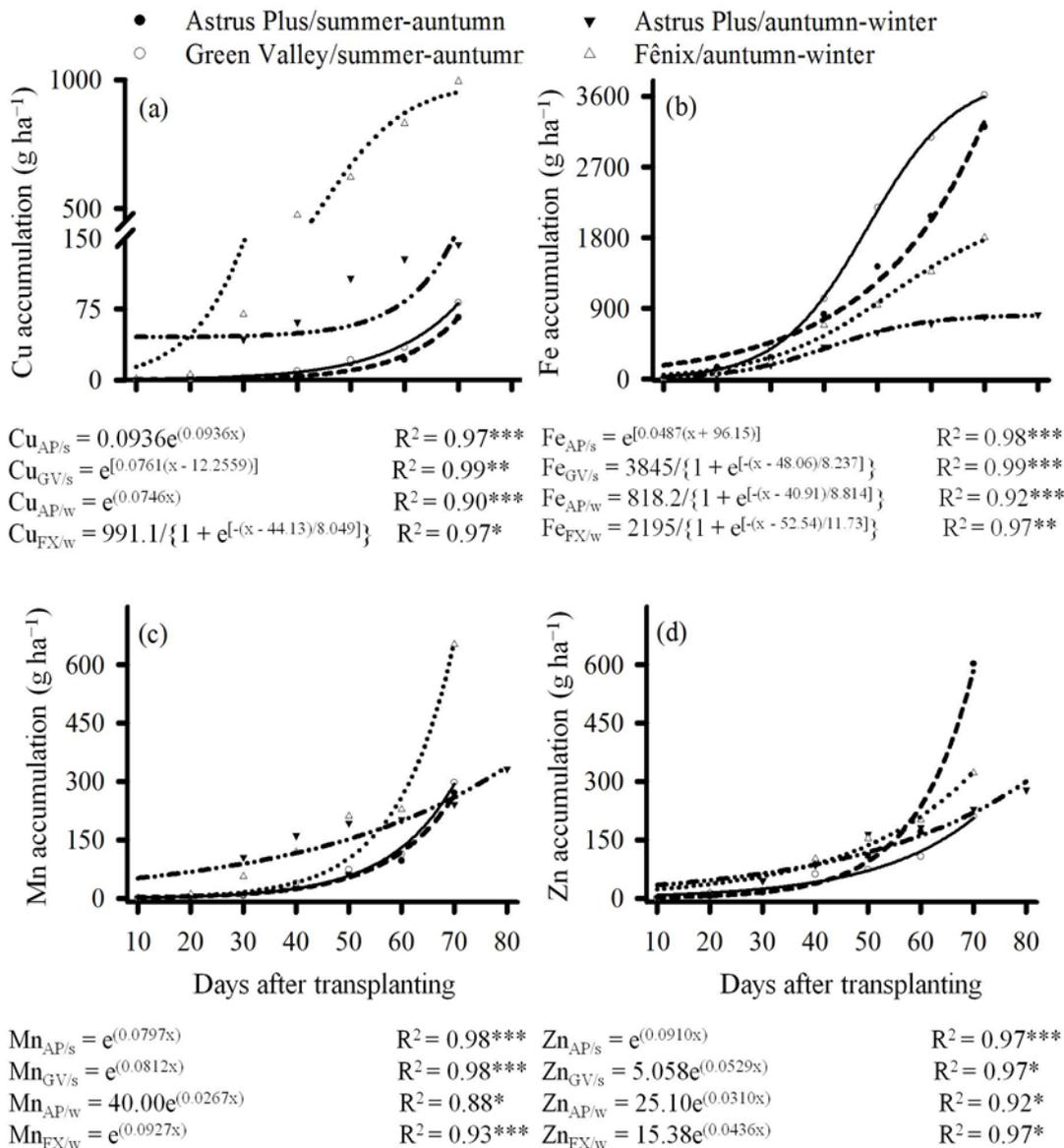


Figure 4. Copper (a), iron (b), manganese (c), and zinc (d) accumulation curves for the cultivars Astrus Plus (AP/s) and Green Valley (GV/s) in the summer-autumn and Astrus Plus (AP/w) and Fênix (FX/w) in the autumn-winter. ***, **, and * are significant at 0.1, 1, and 5%, respectively, by the t-test.

Regarding the order of micronutrient export, Fe was the most exported nutrient, with higher values in the summer-autumn in relation to autumn-winter (Table 3), which can be explained by the higher precipitation during this first growing season (Figure 1). It occurred because the higher precipitation maintained the soil under field capacity, which led to a possible O₂ deficiency. Thus, there is a reduction in soil redox potential and hence iron, which increases the concentration of this nutrient in the plant tissues due to its increased solubility when in the reduced form (PEZESHKI, 2001). The export ranged from 1,674 to 2,106 g Fe ha⁻¹ in the summer-autumn and 448 to 956 g Fe ha⁻¹ in the autumn-winter, which are higher than the

355 g Fe ha⁻¹ observed by Correa, Cardoso, and Claudio (2013).

Zinc was the second micronutrient in the export order, except for the cultivar Green Valley (Table 3). However, the cultivar Astrus Plus in the summer-autumn showed the highest Zn export. Zinc export reached 506 and 205 g Zn ha⁻¹ in the summer-autumn for the cultivars Astrus Plus and Green Valley, respectively. On the other hand, Zn export was similar between cultivars in the autumn-winter, with values of 206 g Zn ha⁻¹ for the cultivar Astrus Plus and 213 g Zn ha⁻¹ for Fênix. However, all these values are above 122 g Zn ha⁻¹ observed by Correa, Cardoso, and Claudio (2013).

Table 3. Amount of micronutrients accumulated[†] in cabbage heads and outer leaves and harvest index for the cultivars Astrus Plus and Green Valley in the summer-autumn and Astrus Plus and Fênix cultivars in the autumn-winter.

Nutrient	Accumulation (g ha ⁻¹)		Harvest index (%)	Accumulation (g ha ⁻¹)		Harvest index (%)
	Heads	Outer leaves		Heads	Outer leaves	
Summer-autumn						
	Astrus Plus			Green Valley		
Cu	29 ± 2.7	40 ± 5.5	42 ± 4.6	26 ± 1.7	56 ± 11.8	32 ± 3.5
Fe	2,106 ± 145.2	1,104 ± 41.5	66 ± 2.1	1,674 ± 86.0	1,940 ± 238.7	47 ± 2.9
Mn	154 ± 11.1	118 ± 5.2	57 ± 1.3	109 ± 16.2	183 ± 34.6	37 ± 1.3
Zn	506 ± 89.2	97 ± 15.6	84 ± 3.3	113 ± 15.2	98 ± 10.1	54 ± 2.0
Autumn-winter						
	Astrus Plus			Fênix		
Cu	67 ± 3.2	326 ± 34.1	17 ± 1.9	64 ± 4.4	930 ± 66.9	7 ± 0.1
Fe	448 ± 25.8	373 ± 34.1	55 ± 3.4	956 ± 261.6	849 ± 132.6	52 ± 6.1
Mn	162 ± 5.1	171 ± 1.4	49 ± 0.9	195 ± 10.8	457 ± 21.6	30 ± 1.4
Zn	203 ± 7.9	72 ± 2.5	74 ± 1.2	213 ± 11.0	104 ± 10.9	67 ± 3.4

[†]Mean ± standard deviation.

Manganese was the third micronutrient in the export order and showed a small variation in the amount exported for the cultivar Astrus Plus as a function of growing seasons, with values of 154 and 162 g Mn ha⁻¹ in the summer-autumn and autumn-winter, respectively (Table 3). The cultivar Fênix was superior to all cultivars in relation to the export, with 195 g Mn ha⁻¹, while Green Valley was inferior, with 115 g Mn ha⁻¹. Correa, Cardoso, and Claudio (2013) found an extraction of 127 g Mn ha⁻¹, which was due to the lower DM production in comparison to the present study.

Copper was the last micronutrient in the export order, with the highest values observed in the autumn-winter (Table 3). It may be related to the higher precipitation during summer-autumn (Figure 1), which maintained the soil continuously under field capacity. Thus, there was possible a reduction in the redox potential, which provided a reduction in SO₄²⁻ to HS⁻ and precipitation of Cd and Cu in the form of sulfide minerals, which have a low solubility (PAN et al., 2016). Thus, the export in the autumn-winter was 64 and 67 g Cu ha⁻¹ for the cultivars Astrus Plus and Fênix, respectively. However, the cultivars Astrus Plus and Green Valley had values of 29 and 26 g Cu ha⁻¹ in the summer-autumn, respectively, which are higher than the 16 g Cu ha⁻¹ observed by Correa, Cardoso, and Claudio (2013).

As observed for macronutrients, the cultivar Astrus Plus showed the highest harvest indices for all micronutrients (Table 3). The values ranged from 54 to 84% for Zn, 46 to 66% for Fe, 30 to 57% for Mn, and 6 to 44% for Cu between cultivars and growing seasons. Thus, greater attention should be given to soil Fe and Zn contents since they present a larger partition for leaves that comprise cabbage head.

CONCLUSIONS

Dry matter and nutrient accumulation are variable according to growing season and cultivar.

The highest DM and nutrient accumulation rates occur during the last ten days of the cycle.

Fertilizations with N, P, K, Fe, and Zn should receive more attention due to higher harvest indices.

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