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Dynamics of micronutrient accumulation and export in the "BRS Vitória" vineyard in the São Francisco valley

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ABSTRACT

Fruit growing in the São Francisco Valley stands out in Brazilian agriculture, especially for the production of grapevines, such as the cultivar 'BRS Vitória'. The objective of this study was to evaluate dry and fresh matter accumulation and to determine micronutrient accumulation rate for the grapevine variety 'BRS Vitória'. The experiment was carried out in Petrolina, PE, Brazil, in a randomized block design, with eight evaluation periods and four replicates. Plant collections were carried out at 15, 30, 45, 60, 75, 90, 105 and 120 days after pruning (DAP). Accumulations of Fe, Zn, Mn and Cu, dry matter and fresh matter, in branches, leaves, fruits and total throughout the cycle were analyzed. The results showed that dry matter accumulation was significant between 45 and 90 DAP, especially in fruits. Micro-nutrients showed an increasing accumulation up to 90 DAP, with iron being the most required, followed by zinc, manganese and copper. Nutrient export was highest for iron, highlighting the need to replace this nutrient in the soil.

Keywords: Accumulation of micronutrients, Export of micronutrients, Mineral nutrition.

Dinâmica de acumulação e exportação de micronutriente na videira "BRS Vitória" no vale do São Francisco

RESUMO

A fruticultura no Vale do São Francisco destaca-se na agricultura brasileira, especialmente pela produção de videiras, como a cultivar BRS Vitória. Este trabalho teve como objetivo avaliar o acúmulo de matéria seca e fresca, e determinar a marcha de acúmulo dos micronutrientes para a variedade BRS Vitória. O trabalho foi realizado em Petrolina-PE, em delineamento experimental blocos casualizados, com oito períodos de avaliação e quatro repetições. As coletas das plantas foram realizadas aos 15, 30, 45, 60, 75, 90, 105 e 120 dias após poda (DAP). Foram analisados o acúmulo de Fe, Zn, Mn e Cu, matéria seca e fresca, ramo, folha, fruto e total ao longo do ciclo. Os resultados mostraram que o acúmulo de matéria seca foi significativo entre 45 e 90 dias após a poda, com destaque para os frutos. Os micronutrientes apresentaram acúmulo crescente até os 90 DAP, com o ferro sendo o mais demandado, seguido pelo zinco, manganês e cobre. A exportação de nutrientes foi mais alta para o ferro, evidenciando a necessidade de reposição deste nutriente no solo.

Palavras-chave: Acúmulo de micronutrientes, Exportação de micronutrientes, Nutrição mineral.

1. Introduction

Fruit growing in the São Francisco Valley occupies a prominent position in Brazilian agriculture, being a reference in production and export of tropical and subtropical fruits. Located in northeastern Brazil, this semi-arid region has unique climatic conditions, such as high luminosity, low rainfall, and efficient use of irrigation, which favor the cultivation of various crops (Santos Júnior et al., 2024). In this context, grapevine production has stood out as one of the main agricultural activities, significantly contributing to local economic development (Leão et al., 2020).

Among the varieties cultivated in the region, ‘BRS Vitória’ has aroused great interest due to its innovative characteristics, high commercial value and excellent adaptability to the semi-arid environment (Maia et al., 2014). These qualities make this cultivar a promising alternative to serve both the domestic and the foreign markets, consolidating itself as a strategic option for regional viticulture (Machado and Santos, 2020).

To ensure the production efficiency of this crop, proper nutritional management plays an essential role, with fertigation being one of the main technologies employed. This system, which combines the application of soluble fertilizers with irrigation, allows for more precise, localized and efficient nutrition throughout the production cycle, maximizing the use of water and nutritional resources and contributing to the reduction of environmental impacts and to the sustainability of agricultural production (Silva et al., 2018).

Another determining factor for the success of cultivation is the knowledge on nutrient absorption rate, which describes the dynamics of nutrient accumulation by plants throughout their development (Bagagim et al., 2022). This understanding is essential for the definition of more efficient nutritional management strategies, ensuring greater fruit production and quality and optimizing yield.

Despite the expansion of viticulture in the São Francisco Valley and the prominence of the 'BRS Vitória' cultivar for its adaptability to the semiarid environment, there are still gaps in understanding the dynamics of micronutrient absorption and export throughout the production cycle. The lack of detailed information on the periods of greatest demand for elements such as iron, zinc, manganese, and copper can compromise the effectiveness of nutritional management and fertigation.

Consequently, the study was based on the hypothesis that the 'BRS Vitória' grapevine, grown in the semiarid conditions of the São Francisco Valley, exhibits distinct variations in micronutrient absorption and export throughout its production cycle. These variations reflect the different physiological requirements of the plant at each stage of development and can be optimized through nutritional management tailored to the crop's growth rate, promoting the rational use of fertilizers and contributing to the sustainability of regional viticulture. There-fore, the present study aims to evaluate dry and fresh matter accumulation and to determine the micronutrient accumulation rate for the grapevine variety ‘BRS Vitória’.

2. Material and Methods

The experiment was carried out in the Maria Tereza Project, located in the city of Petrolina, PE, Brazil, at the Castro Farm, at the following coordinates: latitude 9°22’ S, longitude 40°56’ W and altitude of 420 m, in a 5-year-old vineyard, with the grapevine ‘BRS Vitória’ grafted on the SO4 rootstock. The soil of the area has a sandy loam texture. According to Köppen’s classification, the climate of the region is BSh’, that is, very hot semi-arid and with a rainy season in the summer extending to early autumn.

Prior to pruning, the soil was sampled for chemical and physical analysis, with representative composite samples collected in the 0.00-0.20 m layer and sent to the soil laboratory (Table 1), according to the procedures recommended by Teixeira et al. (2017). After the analysis, the fertilization needed was calculated based on the Manual of Fertilization and Liming for the Pernambuco State.

Table 1. Chemical characteristics of the soil in the experimental area.

Depth	pH	EC_{se}	OM	P	K	Na	Ca	Mg
cm	H_2O	dS m^{-1}	g kg^{-1}	mg kg^{-1}	$cmol_c$ kg^{-1}			
0-20	7.40	0.73	24.30	270.99	0.23	0.05	4.50	2.50

Where: EC_{se}, P, K, Na, Ca, Mg, Al, H+Al, CEC, correspond to electrical conductivity of the soil saturation extract; Available phosphorus; Potassium, Sodium, Calcium, Magnesium, Aluminum, Hydrogen + Aluminum, Base Saturation, Cation Exchange Capacity, respectively

Fertilization was calculated based on the critical level of the crop, with application of 380 kg ha^{-1} of potassium sulfate, 148 kg ha^{-1} of monoammonium phosphate, 314 kg ha^{-1} of calcium nitrate, 30 kg ha^{-1} of zinc sulfate, 6 kg ha^{-1} of boric acid, 254 kg ha^{-1} of magnesium sulfate, 149 kg ha^{-1} of Amiorgan® and 33 kg ha^{-1} of iron sulfate.

All fertilizer applications were split up to 85 days after pruning (DAP). In addition, foliar applications were carried out at 14, 21, 28, 63 and 77 DAP, with boron (160 g L^{-1}), zinc (1000 g L^{-1}) and iron (60 g kg^{-1}), at the following doses: 0.5 L ha^{-1}, 0.3 L ha^{-1} and 0.5 kg ha^{-1}, respectively.

During the crop cycle, the plants were irrigated by 16-mm-diameter drip lines spaced 0.50 m apart with an average flow rate of 2.3 L h^{-1}, also used for fertilization via fertigation. Irrigation depth management was carried out based on the Reference Evapotranspiration (ETo) of the previous day, provided by the automatic agrometeorological station, Davis brand, Vantage Pro 2 model, located about 12 km away from the experimental area, which together with the crop coefficients (kc) of 0.8, 1.1 and 0.6, corresponding to initial, mid-season and late-season phases, respectively (Allen et al., 1998), was used to calculate the daily water requirement of the crop.

The experiment was conducted in a randomized block design, with time being the study factor (15, 30, 45, 60, 75, 90, 105 and 120 DAP), four blocks were used, and each experimental unit consisted of eight plants. Sampling was performed on the five central plants, totaling 64 plants per row and 258 plants in the entire area.

Sampling was carried out every 15 days starting from pruning. On each sampling date, five shoots with lengths determined according to the phenological stage were collected from the five central plants of each experimental unit, resulting in 20 simple samples per treatment. These simple samples were then pooled to form four composite samples per treatment (one per block). The amount of fresh and dry matter (kg ha^{-1}) was estimated according to the following equation:

$$Dry\text{ matter }(kg\ ha^{-1}) = \frac{\left(\left(\frac{DM\text{leaf} + DM\text{fruit} + DM\text{stem}}{5°\ \text{collected shoots}}\right) * \bar{N}\text{shoots} * 1666(\text{plants } ha^{-1})\right)}{1000}$$

Where:

DMleaf: dry matter of leaves (mg);

DMfruit: dry matter of fruits (mg);

DMstem: dry matter of stems (mg);

5° collected shoots: number of shoots evaluated per plant;

$\bar{N}$shoots: average number of shoots per plant (calculated by dividing the total number of shoots counted on five plants by five);

1666 plants ha^{-1}: plant density per hectare;

1000: conversion factor from mg to kg ha^{-1}.

Each individual plant part, stems, leaves, and fruits (when present in each evaluated period), was weighed fresh and washed with distilled water, followed by washing with a 0.1% neutral detergent solution. Next, another rinse with distilled water was performed, after which the material was immersed in a 3% HCl solution. Finally, a last rinse with distilled water was carried out. Subsequently, the samples were dried in a forced-air circulation oven at 65 °C until reaching a constant weight.

After drying, the material was weighed and ground in a Wiley mill for sulfuric digestion, according to the methodology described by Carmo et al. (2000) to determine Fe, Zn, Mn and Cu contents. Accumulations in each part were obtained by multiplying the nutrient content by the respective dry matter of the organ.

The percentage of nutrient extraction was calculated, representing the proportion of a given nutrient absorbed by the plant in relation to the total accumulated throughout the growth cycle.

The percentage of extraction (%) was obtained using the following equation:

$$\text{Extraction percentage (\%)} = \frac{Qi}{Qt}\ x\ 100$$

Where:

Qi: amount of nutrient accumulated at time or growth stage i (g ha^{-1});

Qt: total amount of nutrient accumulated at the end of the plant’s growth cycle.

The data were subjected to analysis of variance and, when significant, as a function of DAP, regression analysis was performed, choosing the model with the highest coefficient of determination, using the statistical program SISVAR 5.6 (Ferreira, 2011).

3. Results and Discussion

Figure 1 shows the increments in fresh matter (A) and dry matter (B) over the days after pruning (DAP) in leaves, branches, fruits and total accumulation (Lv, Br, Fr and To), according to the regression equations and the coefficients of determination (R^2) presented.

It was observed that dry matter and fresh matter accumulation was slow until 30 DAP, but a significant accumulation was recorded between 45 and 90 DAP, due to the growth and filling of fruits. The cultivar ‘BRS Vitória’ reached the peak of dry matter at 90 DAP, with a total of 6,633.46 kg ha^{-1}, and this value was proportionally distributed among the different organs of the plant: 21.04% in the leaves, 87.92% in the fruits and 15.48% in the branches (Figure 1B). In relation to total fresh matter (To), the data were described by a cubic polynomial model, with a maximum accumulation of 35,554.18 kg ha^{-1} reached at 90 DAP, while fruit yield was 28,768.74 kg ha^{-1}.

The micronutrients Zn, Fe, Cu and Mn showed increasing accumulation up to 90 DAP, after which the values decreased until the end of the cycle due to fruit harvest and leaf senescence (Figures 2 and 3).

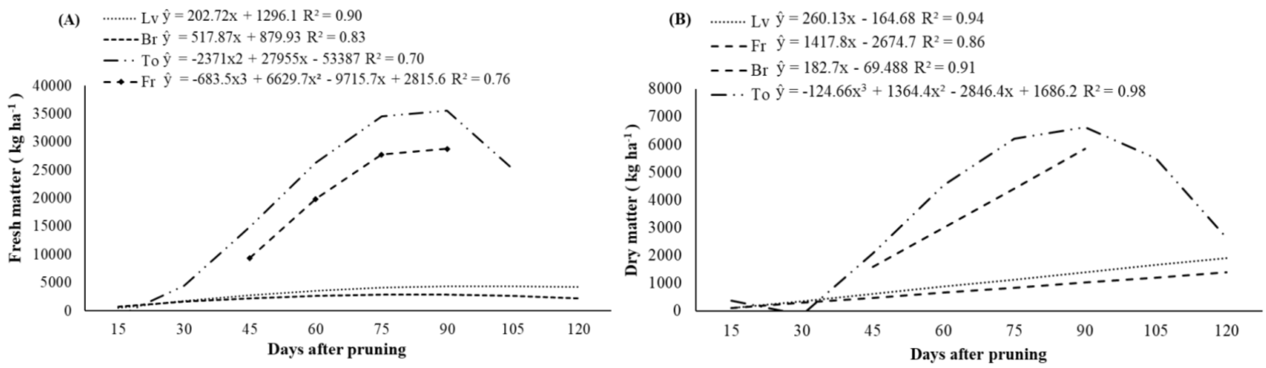

Figure 1. Fresh and dry matter in leaves (Lv), branches (Br), fruits (Fr) and total (To) in 'BRS Vitória' grapevine over the days after pruning.

The cultivar 'BRS Vitória' extracted greater amounts of iron (1,332.67 g ha^{-1}), followed by zinc (349.82 g ha^{-1}), manganese (284.82 g ha^{-1}) and copper (52.95 g ha^{-1}). Thus, micronutrients were most required in the following decreasing order: Fe > Zn > Mn > Cu.

Fe accumulation was 383.43, 188.03 and 953.02 g ha-1 in leaves, branches and fruits, respectively, totaling 1,332.67 g ha^{-1} (Figure 2A). The requirement for Fe between 30 and 90 DAP is associated with the fact that Fe plays a key role in the photosynthetic process and pigmentation of branches, leaves, and fruits (Colzi et al., 2022; Spielmann et al., 2023; Purquerio et al., 2019).

O acúmulo de Fe foi de 383,43, 188,03 e 953,02 g ha^{-1} nas folhas, ramos e frutos, respectivamente, totalizando 1.332,67 g ha^{-1} (Figura 2A). Entre 30 e 90 DAP, a demanda por

Fe é elevada devido ao seu papel fundamental no processo fotossintético e na síntese de pigmentos fotossintéticos, período em que ocorre maior intensidade do metabolismo vegetal (Colzi et al., 2022; Spielmann et al., 2023; Purquerio et al., 2019). Nesse contexto, estudos com videiras demonstram que a concentração de Fe pode variar entre genótipos e diferentes condições climáticas: utilizando Single Nucleotide Polymorphisms (SNPs) como marcadores genéticos, Naegele et al. (2021) identificaram, nos períodos de agosto de 2015 e setembro de 2016, maiores acúmulos de ferro (400,41 ± 86,27 e 484,20 ± 175,14 mg kg^{-1}, respectivamente), especialmente em regiões semiáridas, onde a disponibilidade de Fe no solo é elevada e sua absorção pode ser intensificada em determinados genótipos.

The accumulation of Fe was 383.43, 188.03, and 953.02 g ha^{-1} in leaves, stems, and fruits, respectively, totaling 1,332.67 g ha^{-1} (Figure 2A). Between 30 and 90 DAP, Fe demand is high due to its key role in the photosynthetic process and the synthesis of photosynthetic pigments, a period marked by the highest intensity of plant metabolism (Colzi et al., 2022; Spielmann et al., 2023; Purquerio et al., 2019). In this context, studies on grapevines have shown that Fe concentration can vary among genotypes and different climatic conditions. Using Single Nucleotide Polymorphisms (SNPs) as genetic markers, Naegele et al. (2021) identified higher iron accumulations in August 2015 and September 2016 (400.41 ± 86.27 and 484.20 ± 175.14 mg kg^{-1}, respectively), especially in semi-arid regions where soil Fe availability is high and its uptake may be intensified in certain genotypes.

The second micronutrient most required by grapevine was Zn (Figure 2B), with a total accumulation of 349.82 g ha^{-1}, distributed in the leaves (202.87 g ha^{-1}), fruits (138.31 g ha^{-1}) and branches (59.03 g ha^{-1}) throughout the cycle. The period between 45 and 70 DAP represented approximately 47.46% of the total accumulated. Fruits exported 39.78% of this total, highlighting the importance of Zn in the synthesis of auxins, hormones responsible for cell growth and division, besides promoting flower differentiation and development (Bagagim et al., 2022; Conduta et al., 2020). It also plays an essential role in physiological processes, such as the activation of enzymes involved in the biosynthesis of pigments and in the regulation of cellular respiration, crucial factors for the visual and functional development of fruits (Conduta et al., 2020).

Zn was the second most required micronutrient by the 'BRS Vitória' grapevine, with a total accumulation of 349.82 g ha^{-1}, distributed among leaves (202.87 g ha^{-1}), fruits (138.31 g ha^{-1}), and stems (59.03 g ha^{-1}) throughout the cycle (Figure 2B). Between 45 and 70 DAP, a period of intense growth and floral differentiation, approximately 47.46% of the total Zn accumulation occurred, with 44.9% exported by the fruits, highlighting the importance of Zn in auxin synthesis, cell growth, and fruit development.

Zn accumulation was more pronounced in leaves than in fruits, indicating that most of the nutrient remains in the vegetative tissue. This distribution follows stages of intense cell division and tissue growth, reflecting the physiological role of Zn as an enzymatic activator, regulator of vegetative growth, and promoter of flower and pigment formation, in addition to its participation in photosynthetic and respiratory processes (Bagagim et al., 2022; Conduta et al., 2020). The average Zn concentrations in combined leaf and petiole samples collected in 2015 and 2016 from an F_1 Vitis population were 20.78 ± 3.95 and 26.12 ± 5.88 mg kg^{-1}, respectively (Naegele et al., 2021), reinforcing the absorption and distribution pattern of this micronutrient.

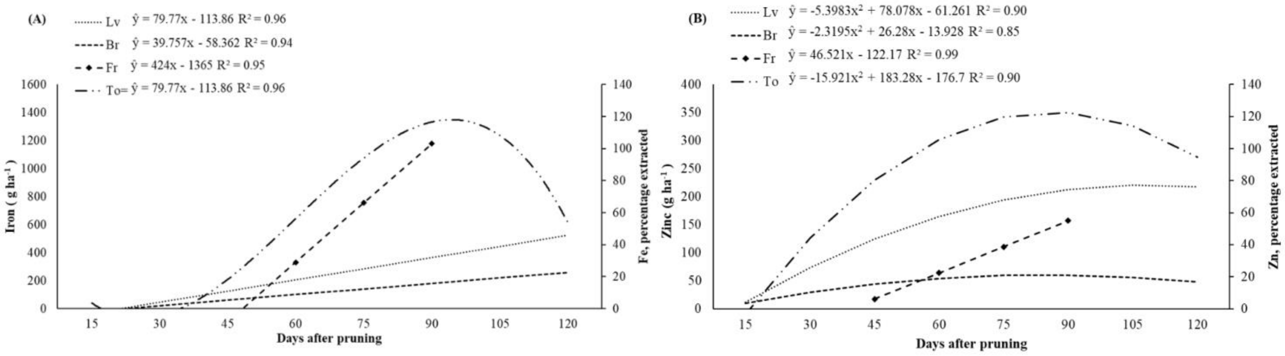

Figure 2. (A) Accumulation of iron (Fe); (B) Accumulation of zinc (Zn), and percentage extracted over the days after pruning in leaves (Lv), branches (Br), fruits (Fr) and total (To).

Leaves were the main storage organs of manganese (Mn), accumulating 180.70 g ha^{-1}, followed by fruits (92.52 g ha^{-1}) and branches (49.71 g ha^{-1}), totaling 284.82g ha^{-1} throughout the production cycle (Figure 3A).

Mn accumulation in the leaves was 51.98%, which highlights the importance of this element for grapevine, especially in the synthesis of chlorophyll, contributing to the maintenance of leaf green color (Bagagim et al., 2022; Cesco et al., 2020). In addition, Mn plays an essential role in reducing oxidative stress by activating the enzyme superoxide dismutase (Mn-SOD), which acts in defense against reactive oxygen species (ROS). This antioxidant function is particularly relevant for grapevines in the São Francisco Valley region, where adverse environmental conditions, such as high light intensity and high temperatures, can generate high oxidative stress (Purquerio et al., 2019; Colzi et al., 2022).

Approximately 40% of the Mn extracted in the cycle was accumulated during the period between 45 and 90 DAP. This absorption pattern suggests that Mn application should be adjusted to this critical phase of grapevine development, optimizing fertilizer efficiency and minimizing losses.

Cu was the fourth most required micronutrient, with a total accumulation at 90 DAP of 44.65 g ha^{-1} in leaves, 6.09 g ha^{-1} in stems, and 7.37 g ha^{-1} in fruits, totaling 52.95 g ha^{-1} throughout the cycle (Figure 3B). Leaves concentrated 84.81% of the total, highlighting the importance of Cu in the functioning of enzymes such as polyphenol oxidase and superoxide dismutase, which are essential for protection against free radicals (Colzi et al., 2022). Only 16.5% of the accumulated Cu was exported by the fruits, indicating that most of the micronutrient remains in the plant. Its accumulation follows the increase in dry matter (DM) and fresh matter (FM), which was slow until 30 DAP and intensified between 45 and 90 DAP, during the period of fruit growth and filling (Figure 1A and B).

Its function is related to enzymatic activity and protection against ROS. Naegele et al. (2021) observed average foliar Cu concentrations of 6.20 ± 2.43 and 6.12 ± 1.25 mg kg^{-1} in an F_1 Vitis population in 2015 and 2016, respectively, confirming the nutrient's stability during vegetative development.

Cu was the fourth most required micronutrient, with the following values accumulated at 90 DAP: 44.65 g ha^{-1} in leaves, 6.09 g ha^{-1} in branches, 7.37 g ha^{-1} in fruits, totaling 52.95 g ha^{-1} throughout the cycle (Figure 3B). Leaves accumulated 84.81% of the total, which points to their relevance in the functioning of enzymes such as polyphenol oxidase and superoxide dismutase, essential in the protection against free radicals (Colzi et al., 2022).

Table 2 presents the extraction and export of micronutrients in fresh grapes of the cultivar 'BRS Vitória', highlighting the difference between the amount of nutrients removed from the plant and the amount that is effectively exported by the fruit.

Extracted micronutrients represent the amount absorbed by the plant throughout the production cycle to sustain vegetative growth and fruit development, whereas exported micronutrients correspond to the amount of nutrients removed from the agricultural system with fruit harvest, that is, what does not return to the soil or to the plant. In this context, the difference between the two values indicates the amount of each micronutrient that remains in the vegetative part of the plant (leaves, branches and roots), which can be recycled or need replacement via fertilization.

Fe has the highest export rate compared to the total extracted, with about 88.5% being removed with the fruits. This indicates the need for attention to the replacement of this micronutrient in the soil. Zn and Mn are extracted in relatively large quantities, but only 44.9% and 35.0%, respectively, are exported, suggesting that a significant part is retained in the plant. Cu, on the other hand, has the lowest proportional export, with only 16.5% of the total extracted being removed by the fruits.

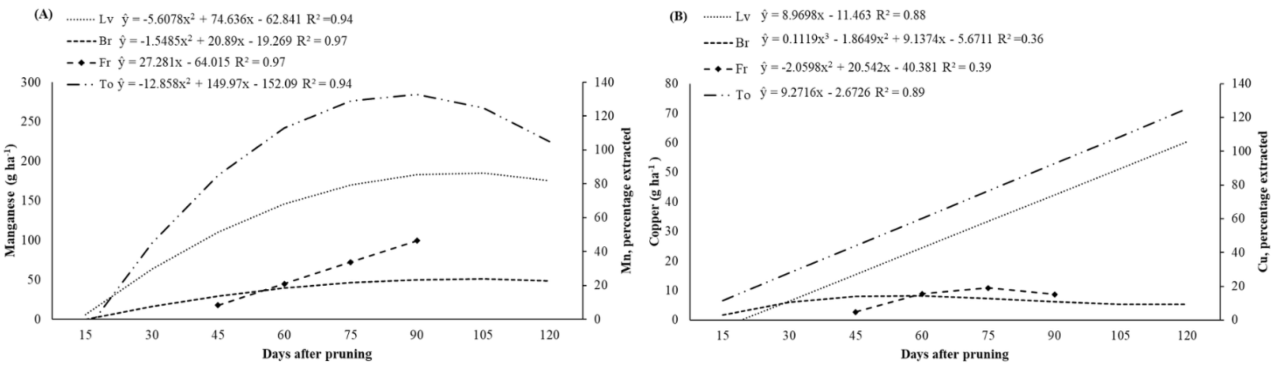

Figure 3. (A) Accumulation of manganese (Mn); (B) Accumulation of copper (Cu), and percentage extracted over the days after pruning in leaves (Lv), branches (Br), fruits (Fr) and total (To).

Table 2. Extraction and export of micronutrients per ton of fresh grapes of the cultivar 'BRS Vitória'.

	Fe	Zn	Mn	Cu
	mg t^{-1} of fresh fruit			
Extraction	469.13	123.15	100.27	18.64
Export	415.02	55.25	35.09	3.07

The nutritional balance of the cultivar 'BRS Vitória' shows that, although micronutrients are markedly extracted by the plant, only a fraction is exported with the fruits. Fe deserves special attention due to its significant removal with harvest, while the other micronutrients can be managed based on recycling within the plant and the content available in the soil. Therefore, the tables show the dynamics of absorption and export of micronutrients in the cultivar 'BRS Vitória', highlighting the importance of considering not only the amount extracted, but also the destination of these nutrients to optimize fertilization practices and nutritional management of the crop.

4. Conclusions

Dry matter accumulation increased up to 90 DAP (harvest).

'BRS Vitória' grapevine cultivated in the São Francisco Valley has the following decreasing order of micronutrient accumulation: Fe>Zn>Mn>Cu.

The greatest demand for iron and zinc by 'BRS Vitória' grapevine occurs in the period from 60 to 90 DAP.

Authors' Contribution

Victor da Silva Carvalho: Investigation, writing-original draft. Samuel Lourival Nunes de Macedo: Investigation, writing-original draft. Amós Cardoso de Meneses: Investigation, writing-original draft. Marina Souza Pereira Matos: Writing-original draft, writing-review andediting. Gilberto Saraiva Tavares Filho: Formal analysis, figure design, writing-review andediting. Fabio Freire de Oliveira: Conceptualization, writing-review and editing. Cicero Antônio de Sousa Araújo: Conceptualization, methodology, formal analysis, writing-review andediting.

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