Pesquisa Agropecuária Brasileira

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

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Received
September 05, 2024

Accepted
April 17, 2025

How to cite
ANDRADE, W.J.M. de; MENEZES, S.M. de; SILVA, G.F. da; VASCONCELOS, M.C. de; SILVA, K.E. da; SILVA, M.M. da; SILVA, E.F. de F. e; SOUZA, C.S. de; LOPES, I.A.P.; SILVA, A.O. da; SOUSA, R.R. Extraction and export of nutrients by sugarcane under pulsed and continuous irrigation. **Pesquisa Agropecuária Brasileira**, v.60, e03892, 2025. DOI: https://doi.org/10.1590/S1678-3921.pab2025.v60.03892.

Mineral Nutrition/ Original Article

Extraction and export of nutrients by sugarcane under pulsed and continuous irrigation

Abstract – The objective of this work was to determine nutrient extraction and export in sugarcane under pulsed and continuous irrigation at five levels of replacement of crop evapotranspiration. The experiment was conducted from 12/12/2019 to 12/22/2020 under field conditions in the municipality of Carpina, in the state of Pernambuco, Brazil. The used experimental design was randomized complete blocks, in a 2x5 factorial arrangement, with two types of irrigation application (pulsed and continuous irrigation) and five levels of replacement of crop evapotranspiration (40, 60, 80, 100 and 120%), with four replicates, totaling 40 experimental units. For pulsed irrigation, five irrigation pulses were defined, with an interval of 40 min between each of them. For the analyses of nutrient extraction and export, plants were collected in the usable area of each experimental plot, at the time of harvest. The isolated factor type of fertigation application significantly influenced the extraction and export of iron, manganese, and zinc, as well as the export of sulfur. Under pulsed irrigation, the descending order of nutrient extraction and export is: K>N>Ca>S>Mg>P>Fe>Zn>Mn>Cu and N>K>Ca>Mg>S>P>Fe>Zn>Mn>Cu, respectively. Under continuous irrigation, the order of extraction and export is: K>N>S>Ca>Mg>P>Fe>Zn>Mn>Cu and N>K>Mg>Ca>S>P>Fe>Zn>Cu>Mn, respectively.

Index terms: *Saccharum officinarum*, fertigation, plant nutrition.

Extração e exportação de nutrientes pela cana-de-açúcar sob irrigação pulsada e contínua

Resumo – O objetivo deste trabalho foi determinar a extração e a exportação de nutrientes em cana-de-açúcar sob irrigação pulsada e contínua a cinco níveis de reposição de evapotranspiração da cultura. O experimento foi conduzido de 12/12/2019 a 22/12/2020 em condições de campo, no município de Carpina, no estado de Pernambuco, Brasil. O delineamento experimental utilizado foi em blocos ao acaso, em arranjo fatorial 2x5, com dois tipos de aplicação de irrigação (pulsada e contínua) e cinco níveis de reposição da evapotranspiração da cultura (40, 60, 80, 100 e 120%), com quatro repetições, o que totalizou 40 unidades experimentais. Para a irrigação por pulsos, foram definidos cinco pulsos de irrigação com intervalo de 40 min entre cada um. Para as análises de extração e exportação de nutrientes, as plantas foram coletadas na área útil de cada parcela experimental, no momento da colheita. O fator isolado tipo de aplicação da fertirrigação influenciou significativamente as extrações e as exportações de ferro, manganês e zinco, bem como a exportação de enxofre. Sob irrigação pulsada, a ordem decrescente de extração e exportação de nutrientes é: K>N>Ca>S>Mg>P>Fe>Zn>Mn>Cu e N>K>Ca>Mg>S>P>Fe>Zn>Mn>Cu, respectivamente. Sob irrigação contínua, a ordem de extração e exportação é: K>N>S>Ca>Mg>P>Fe>Zn>Mn>Cu e N>K>Mg>Ca>S>P>Fe>Zn>Cu>Mn, respectivamente.

Termos para indexação: *Saccharum officinarum*, fertirrigação, nutrição vegetal.

Introduction

The cultivation of sugarcane (*Saccharum officinarum* L.) has been economically important for Brazil since the colonial period, leading the country to currently being the largest producer and exporter of sugar in the world, accounting for approximately 23.6% of production and 38% of global trade (Klein & Luna, 2023; Acompanhamento…, 2024). In this context, irrigation management is important to promote a sustainable agricultural development, based on the rational use of water resources, as well as on the reduction of agricultural inputs and energy.

Among the used water-management methods, drip irrigation is considered the most efficient, as water is supplied directly around the roots of the plant (Mishra et al., 2022), including benefits such as a lower evaporation, infiltration, and percolation (Yang et al., 2020). Another common technique is pulsed irrigation, used to support irrigation management by fractioning the daily irrigation layer into shorter irrigation cycles, followed by a rest phase and another short irrigation cycle until the entire volume of water is applied (García-Prats & Guillem-Picó, 2016; Zamora et al., 2019).

Regarding fertilizer use, the sugarcane crop is ranked third in the Brazilian territory, only behind soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.), accountable for about 11% of all fertilizer exported to the country (Brasil, 2023). Therefore, knowledge of plant nutritional needs and possible relationships with cultivation techniques, as pulsed irrigation, become of fundamental importance to subsidize crop management strategies.

Other information that can assist in efficient fertilization programs include sugarcane productive behavior and the amount of nutrients accumulated in the plant (Guimarães et al., 2019; Havlin & Heiniger, 2020). Increases in the efficiency of input use reflect in improvements in the nutritional relationships of the crop and the availability of nutrients in a readily assimilable form, allowing of plants to reach their maximum productive capacity and, consequently, an increased productivity.

The objective of this work was to determine nutrient extraction and export in sugarcane under pulsed and continuous irrigation at five levels of replacement of crop evapotranspiration (ETc).

Materials and Methods

The experiment was conducted from 12/12/2019 to 12/22/2020 under field conditions at Estação Experimental de Cana-de-açúcar de Carpina, a sugarcane research unit of Universidade Federal Rural de Pernambuco, located in the municipality of Carpina, in the forest zone region of the state of Pernambuco, Brazil (7º51'24.31"S, 35º14'16.97"W, at 180 m altitude).

The climate of the region, according to the Köppen-Geiger's classification, is As, megathermal tropical, i.e., humid tropical (Alvares et al., 2013), with an average annual precipitation of 1,149 mm per year and an average evapotranspiration varying from 1,000 to 1,600 mm per year. During the experiment, the maximum and minimum air temperatures were 33.1 and 21.8°C, respectively, and the average relative humidity was 79.8%. The soil of the experimental area was classified as an Argissolo Amarelo distrófico abrupto (Santos et al., 2018), corresponding to a hyperdystric abruptic Acrisol (IUSS Working Group WRB, 2015). The physicochemical characterization of the soil at the depths of 0.0–0.2 and 0.2–0.4 m are presented in Table 1.

The used experimental design was a randomized complete block, in a 2x5 factorial arrangement, with two types of irrigation application (pulsed and continuous irrigation) and five layers of replacement of ETc (40, 60, 80, 100, and 120%), with four replicates, totaling 40 experimental units. For pulsed irrigation application, five irrigation pulses were defined, with an interval of 40 min between each of them.

The experimental plot had four combined planting furrows of 1.40 m + 0.60 m, measuring 7.0 m in length, resulting in 56 m^2 per experimental unit. The two central furrows were used for evaluations, disregarding 1.0 m from the ends, totaling 20 m^2 of usable area.

The soil was prepared conventionally. The tebuthiuron herbicide (2.0 L ha^{-1}) was applied to control weeds and crop residues, then a subsoiler was used for soil loosening at deeper levels, followed by harrowing and furrowing at a 25 cm depth for plowing and planting of sugarcane seedlings. To correct soil acidity, liming was carried out by applying 0.5 Mg ha^{-1} dolomitic limestone before the implementation of the crop. Fertilization was based on the chemical analysis of the soil, considering the nutritional demand of sugarcane (Oliveira et al., 2016).

DOI: 10.1590/S1678-3921.pab2025.v60.03892

Mineral fertilization was applied conventionally to the cane-plant at the time of planting, using 40 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5, and 60 kg ha^{-1} K_2O in the forms of urea, single superphosphate, and potassium chloride, respectively. Top dressing was performed via irrigation water, using 40 kg ha^{-1} N, in the form of urea, in ten weekly applications from August to October. The RB041443 sugarcane cultivar was cultivated, distributed in furrows at a depth of 0.15 m, with a density of 12 buds per linear meter.

The method of localized irrigation by subsurface drip was used, with in-line self-compensating and anti-drain emitters with a nominal flow rate of 1.0 L h^{-1}, spaced at 0.50 m, at a soil depth of 0.20 m. The drip tubes had a nominal diameter of 16 mm, spaced at 2.0 m. For the pumping system, a 3.0 hp centrifugal pump was used. The fertilizers were injected using a Venturi tube. The treatments were applied individually through a set of ten ball-type registers that controlled the water flow to the experimental plots.

Complementary irrigation was carried out in August, September, and October, that is, in the months with the lowest rainfall index in the region (Figure 1). During these months, irrigation was applied daily according to the water needs of sugarcane, based on ETc, and to each treatment.

To obtain the ETc, the class A tank method was used (Doorenbos & Pruitt, 1977), considering the following equation:

$$ETc = ECA \times Kp \times Kc \times Kl$$

where ETc is crop evapotranspiration in millimeters per day; ECA is the evaporation of the class A tank, also in millimeters per day; Kp is the coefficient of the class A tank, dimensionless; Kc is the crop coefficient, also dimensionless; and Kl is the location coefficient of the drip irrigation system, dimensionless.

The Kc data used followed the recommendation of Doorenbos & Kassam (1994), based on each stage of crop development. The Kp values were obtained from the data of wind speed, relative air humidity, and evaporation of the class A tank (Doorenbos & Pruitt, 1977).

At 330 days after planting (DAP), irrigation was suspended to cause water stress in the sugarcane crop, aiming to intensify sugar (sucrose) accumulation until the time of harvest, as well as to induce maturation and increase sugar concentration; the sugarcane plants were harvested at 365 DAP.

For the analyses of nutrient extraction and export, four plants were collected from the usable area of each experimental plot, at the time of harvest, being separated into stalk and aerial part. Then, the samples were crushed in an industrial forage harvester and taken for drying in a forced circulation oven, at 65°C, until obtaining a constant mass. Afterwards, the samples were processed in a Willey-type mill and then subjected to the acid digestion process for later quantification of the extraction and export of the following nutrients: nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, copper, manganese, and zinc.

Table 1. Physicochemical characterization of the soil of the experimental area, at different depths, before the installation of the experiment in 2019 in the municipality of Carpina, in the state of Pernambuco, Brazil[(1)].

Chemical characterization													
Layer (m)	pH (H_2O)	P (mg dm^{-3})	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	Al^{+3}	$H^{+}+Al^{+3}$	SB	CEC	m	V	OM (g kg^{-1})
			(cmol$_c$ dm^{-3})								(%)		
0–0.20	5.8	12	5.16	1.05	0.06	0.12	0.0	2.8	6.39	9.19	0.0	69.53	1.98
0.20–0.40	5.9	12	2.31	0.93	0.04	0.07	0.0	3.0	3.35	6.35	0.0	52.76	1.88
Physical characterization													
	Sand	Silt	Clay		Texture		Ds	Dp	θ_{CC}		θ_{PMP}		
	(g kg-1)				-		(g cm^{-3})		(m^3 m^{-3})				
0–0.20	709	120	171		Sandy loam		1.36	2.63	0.15		0.10		
0.20–0.40	710	99	191		Sandy loam		1.31	2.56	0.18		0.12		

[(1)]SB, sum of bases; CEC, cation exchange capacity; m, aluminum saturation; V, base saturation; OM, organic matter; Ds, soil density; Dp, particle density; and θ_{CC} and θ_{PWP}, volumetric soil moisture at field capacity and at permanent wilting point, respectively.

Nitrogen was extracted by open digestion using the digestor block as a heat source and a mixture of sulfuric acid (H_2SO_4), hydrogen peroxide (H_2O_2), and digestor mixture for dry matter digestion. Nutrients P, K, Ca, Mg, S, Fe, Cu, Mn, and Zn were digested in a closed system using a microwave oven as a heat source and nitric acid (HNO_3) according to Silva (2009).

The methods used to determine the total concentration of each nutrient were: steam distillation method (Kjeldahl) for N; flame photometry method for K; molybdo-vanadate colorimetric method for P; barium sulfate turbidimetric method for S; and atomic absorption spectrophotometry for Ca, Mg, Zn, Cu, Fe, and Mn (Bezerra Neto & Barreto, 2011).

The chemical analyses indicated the concentrations of each nutrient, which were multiplied by the dry mass of each part of the plant (stalk and aerial part) for accumulation (extraction) quantification. Nutrient total extraction and export were considered as, respectively, the sum of the accumulation of nutrients in the stalk and aerial part of the sugarcane plant and the amount of nutrients accumulated in the stalks.

The data were subjected to the tests of normality and homoscedasticity and to the analysis of variance by the F-test ($p < 0.05$) using the SISVAR statistical software (Ferreira, 2019). When a significant effect was found for the F-test, the data related to the replacement level of ETc were unfolded through regression analysis ($p < 0.05$). The data related to the types of irrigation application were compared by the Scott-Knott mean test ($p < 0.05$).

Results and Discussion

The analysis of variance showed that the interaction between the types of irrigation application (pulsed and continuous) and irrigation levels (40, 60, 80, 100, and 120% ETc) had a significant effect ($p<0.01$) on the total extraction and export of Ca (Table 2). The extractions of N and Mn by the plants, as well as the exports of N, Mg, and Zn, were significantly influenced, in an isolated way, by the applied irrigation levels. The isolated factor type of fertigation application significantly influenced the extraction and export of Fe, Mn, and Zn, as well as the export of S.

The extraction of N by the sugarcane crop was the highest (114.97 kg ha^{-1}) at the irrigation level corresponding to 99.42% ETc, representing an increase of 27.4% in relation to the lowest value of 90.24 kg ha^{-1}

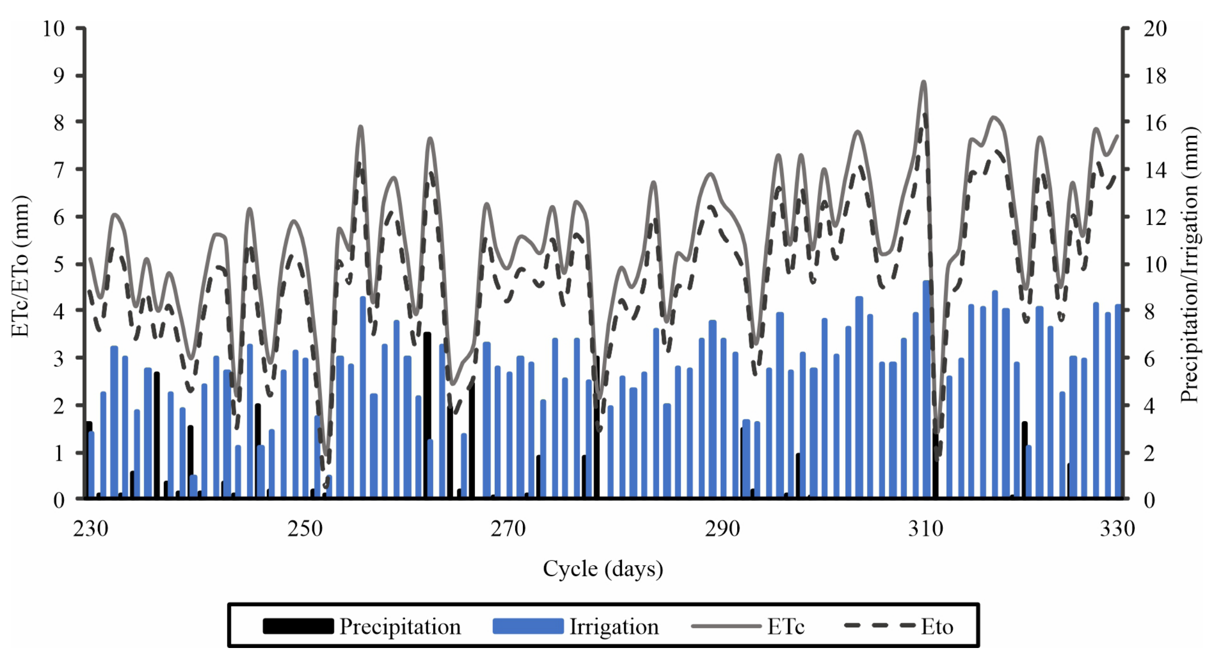


Figure 1. Monitoring of precipitation, irrigation, crop evapotranspiration (ETc) and reference evapotranspiration (ETo) from 08/01/2020 to 10/31/2020 in the municipality of Carpina, in the state of Pernambuco, Brazil.

obtained at the lowest level of 40% ETc (Figure 2 A). Regarding the export of N (Figure 2 B), the highest exported amount was 94.12 kg ha^{-1} at 108.30% ETc, showing an increase of 29.55 in relation to the level of 40% ETc. This information is important since N is an essential macronutrient for plant development, being required in large quantities by the sugarcane crop as it is indispensable for a vigorous root growth, vegetative development, and improved yields and production quality (Costa et al., 2019).

Table 2. Analysis of variance for the total extraction and export (aerial part + stalk) of macronutrients (N, P, K, Ca, Mg, and S) and micronutrients (Fe, Mn, Cu, and Zn) by RB041443 sugarcane (*Saccharum officinarum*) cultivar, as a function of the types of irrigation application and replacement levels of crop evapotranspiration in the municipality of Carpina, in the state of Pernambuco, Brazil[(1)].

Source of variation	DF	Nutrient extraction					
		Mean square – Macronutrient					
		N	P	K	Ca	Mg	S
Application type (T)	1	0.055^{ns}	2.965^{ns}	620.550^{ns}	499.424**	29.739^{ns}	13.865^{ns}
Level (L)	4	999.763**	27.676^{ns}	93.435^{ns}	338.285**	30.324^{ns}	31.317^{ns}
T x L	4	20.237^{ns}	1.573^{ns}	2.0123^{ns}	57.966**	3.574^{ns}	2.295^{ns}
Block	3	64.803^{ns}	5.075^{ns}	309.718^{ns}	8.360^{ns}	3.311^{ns}	2.475^{ns}
Residue	27	165.999	14.008	417.686	13.431	25.389	13.645
CV (%)		12.04	14.71	15.09	8.05	12.8	8.64
Source of variation	DF	Mean square – Micronutrient					
		Fe	Mn	Cu	Zn		
Application type (T)	1	24.180*	0.043**	0.000^{ns}	0.151*		
Level (L)	4	3.002^{ns}	0.010**	0.001^{ns}	0.047^{ns}		
T x L	4	9.384^{ns}	0.001^{ns}	0.001^{ns}	0.021^{ns}		
Block	3	2.521^{ns}	0.003^{ns}	0.003^{ns}	0.093^{ns}		
Residue	27	4.054	0.002	0.002	0.027		
CV (%)		27.67	23.22	28.05	21.08		
		Nutrient export					
Source of variation	DF	Mean square – Macronutrient					
		N	P	K	Ca	Mg	S
Application type (T)	1	33.874^{ns}	2.025^{ns}	92.994^{ns}	133.444**	0.001^{ns}	50.019*
Level (L)	4	851.640**	23.339^{ns}	9.660^{ns}	195.653**	39.902*	11.022^{ns}
T x L	4	19.690^{ns}	1.611^{ns}	0.587^{ns}	25.238*	1.834^{ns}	1.022^{ns}
Block	3	8.283^{ns}	7.100^{ns}	313.397^{ns}	12.999^{ns}	2.333^{ns}	4.395^{ns}
Residue	27	142.73	11.339	260.493	7.89	12.563	5.708
CV (%)	%	13.83	15.91	19.27	10.07	12.4	9.04
Source of variation	DF	Mean square – Micronutrient					
		Fe	Mn	Cu	Zn		
Application type (T)	1	18.401*	0.025**	0.000^{ns}	0.009**		
Level (L)	4	5.537^{ns}	0.005^{ns}	0.001^{ns}	0.002*		
T x L	4	6.664^{ns}	0.000^{ns}	0.000^{ns}	0.003^{ns}		
Block	3	2.451^{ns}	0.003^{ns}	0.001^{ns}	0.000^{ns}		
Residue	27	3.914	0.002	0.001	0.001		
CV (%)		26.83	33.77	28.19	17.92		

[(1)]DF, degrees of freedom. ** and *Significant at 1 and 5% probability, respectively. ^{ns}Nonsignificant.

DOI: 10.1590/S1678-3921.pab2025.v60.03892

According to the obtained results, the lowest extraction and export of N by the crop were observed with the replacement level of 40% ETc, a limitation imposed by the water conditions to which the plants were subjected. This shows how, although nutrient extraction and export by plants can be influenced by various factors, water availability stands out. Martins et al. (2014) concluded that water availability is essential for the nutritional balance of crops, being fundamental in the metabolic and physiological processes of plants, mainly acting in the photosynthetic capacity, but also in processes related to the absorption and transport of nutrients between organs, metabolic activity, and gas exchanges.

In the literature, N extraction and export were, respectively, 260 and 167.4 kg ha^{-1} for RB92579 sugarcane under full irrigation (Oliveira et al., 2010). When the same sugarcane variety was evaluated under rainfed conditions, the value of exported N was 147 kg ha^{-1} (Oliveira et al., 2016). Other authors obtained values of 91.89 and 124.75 kg ha^{-1} (Salviano et al., 2017) and of 171 and 122 kg ha^{-1} (Lira et al., 2019) for N extraction and export, respectively. This wide range of nutrient extraction values in comparison with that of the present work highlights the relevance of studies on nutrient extraction and export for different sugarcane cultivars and varieties, mainly under irrigated conditions.

According to the unfolding of the studied factors, the irrigation levels applied within the types of irrigation management (pulsed and continuous) resulted in significant differences in the extraction (Figure 3 A) and export (Figure 3 B) of Ca by the sugarcane plants.

The highest extraction of Ca was 56.87 kg ha^{-1}, obtained under pulsed irrigation at the irrigation level corresponding to 92.8% ETc, representing an increase of 62.2% in relation to the value of 35.06 kg ha^{-1} at the lowest level of 40% ETc (Figure 3 A). However, when the plants were irrigated continuously, the highest nutrient extraction was 45.49 kg ha^{-1} at 103.95% ETc, evidencing an increase of 26.04% in comparison with the value obtained at the level of 40% ETc.

The highest values of Ca extraction and export under pulsed irrigation are possibly due to the maintenance of a more constant soil moisture throughout the day with this type of irrigation management. This, associated with the low mobility of the nutrient in the soil (Malavolta et al., 1997), favored a greater Ca solubilization and, consequently, availability in the soil solution, increasing its extraction and export.

As observed in the present work, Menezes et al. (2020) also found that the accumulation of Ca by coriander (*Coriandrum sativum* L.) plants increased under pulsed irrigation, when compared with continuous drip. Likewise, Cruz et al. (2021) reported a greater accumulation of Ca in the peanut (*Arachis hypogaea* L.) crop when the plants were subjected to the pulsed regime. However, González Chavarro et al. (2018) noted that macronutrient absorption curves varied from 58.1 to 84.9 kg ha^{-1} depending on the evaluated cultivar, which shows the importance of studies on recently launched cultivars, as the one analyzed in the present research.

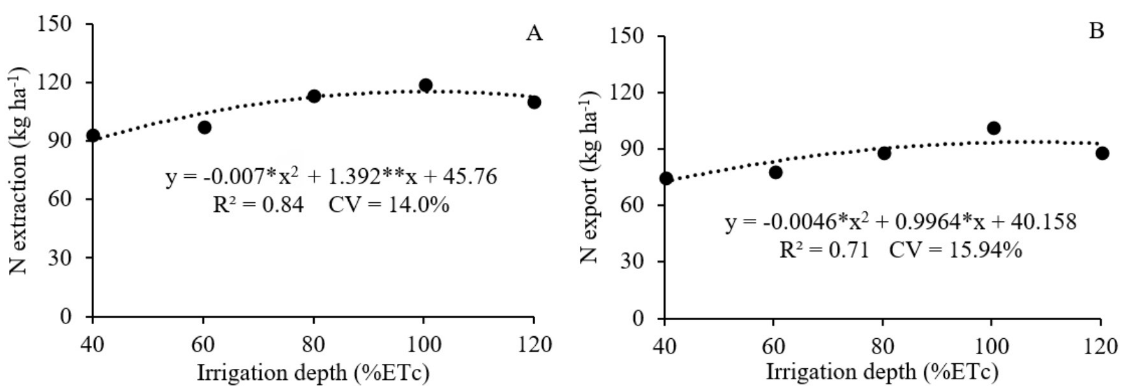


Figure 2. Total extraction (A) and export (B) of nitrogen in a sugarcane (*Saccharum officinarum*) crop as a function of replacement levels of crop evapotranspiration (ETc). ** and *Significant at 0.01 and 0.05 probability, respectively.

DOI: 10.1590/S1678-3921.pab2025.v60.03892

For Mn, the maximum extraction was 0.224 kg ha^{-1}, obtained at an irrigation level of 95% ETc, representing an increase of 67.41% over the value found at the irrigation level of 40% ETc (Figure 4 A). As for the effect of the types of irrigation application, the highest nutrient extraction was 0.224 kg ha^{-1} under pulsed irrigation, representing an increase of 41.77% compared with the value of 0.158 kg ha^{-1} under continuous irrigation.

The movement of Mn^{2+} in the soil to the plant roots occurs through two mechanisms, known as diffusion and root interception, which require that the nutrient be applied close to the root system of the crop (Silva & Berti, 2022). By maintaining the nutrient closer to the plant root zone for a longer time, pulsed irrigation favors Mn absorption and export, avoiding leaching and reducing water losses by percolation. This explains the highest export of Mn by the sugarcane crop under this water regime, which resulted in an increase of 48.26% compared with the amount exported under continuously applied irrigation (Figure 4 B).

According to Zamora et al. (2019), pulsed irrigation has shown promising results in production and product quality, water rationing, and soil moisture maintenance in different crops. However, results may vary according to the used cultivar and the conditions to which the plants are subjected. Silva et al. (2018), for example, evaluating the accumulation of Mn in the aerial part of sugarcane, found an average accumulation of 639 g ha^{-1} Mn, whereas Morais et al. (2022), studying the nutritional status of sugarcane under irrigated conditions, obtained values of 4.7 and 3.4 kg ha^{-1} for the extraction and export of the nutrient, respectively.

As for Fe, continuous irrigation increased nutrient extraction and export by 23.85 and 27.98% (Figure 4 C), respectively, when compared with pulsed irrigation (Figure 4 D). Since the studied soil is well-drained tropical, with a very low Fe concentration in solution and in the exchange complex (Lindsay & Cox, 1985), the availability of water all at once through continuous irrigation likely provided a better solubilization and, consequently, a greater extraction and export of the nutrient by the plants. Silva et al. (2018) evaluated the mineral nutrition of the sugarcane crop under irrigated cultivation and found average Fe extractions of 4.204, 3.434, and 3.143 kg ha^{-1}, respectively, during the cane-plant cycle and the first and second ratoons.

Pulsed irrigation increased the extraction of Zn by the plants by 17.26% when compared with continuously applied irrigation (Figure 4 E). Regarding the export of zinc, the obtained data adjusted to the increasing linear model (Figure 4 F), where the highest nutrient export was 0.168 kg ha^{-1} at the irrigation level of 120%, followed by an increase of 0.0005% for each unit increase of ETc. In their study using sugarcane, Silva et al. (2018) obtained a value of 0.34 kg ha^{-1} exported Zn.

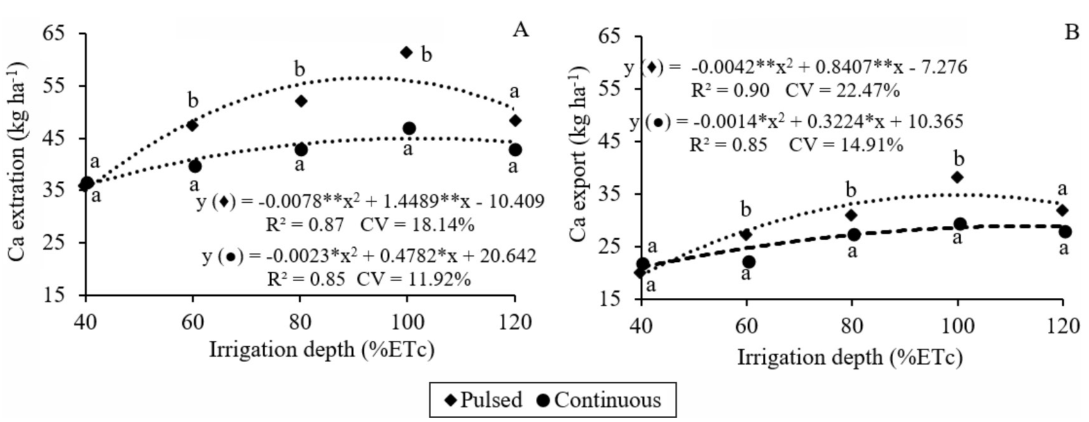


Figure 3. Unfolding of the interaction between factors for total extraction (aerial part + stem) (A) and export (B) of calcium in a sugarcane (*Saccharum officinarum*) crop subjected to different replacement levels of crop evapotranspiration (ETc) and types of irrigation application (continuous and pulsed) in the municipality of Carpina, in the state of Pernambuco, Brazil. Different letters indicate significant differences between the types of irrigation application (pulsed and continuous) by the Scott-Knott test. ** and *Significant at 0.01 and 0.05 probability, respectively.

In relation to S, pulsed irrigation provided the highest nutrient export of 27.55 kg ha^{-1} by the crop, reflecting an increase of 8.83% when compared to the value of 25.3 kg ha^{-1} obtained under continuous irrigation (Figure 5 A). Possibly, the more consistent soil moisture throughout the day due to pulsed irrigation resulted in a lower leaching and, consequently, in a greater availability of S for absorption by plants during the day. Salviano et al. (2017) reported values of 37 and 26 kg ha^{-1} for the extraction and export of S in

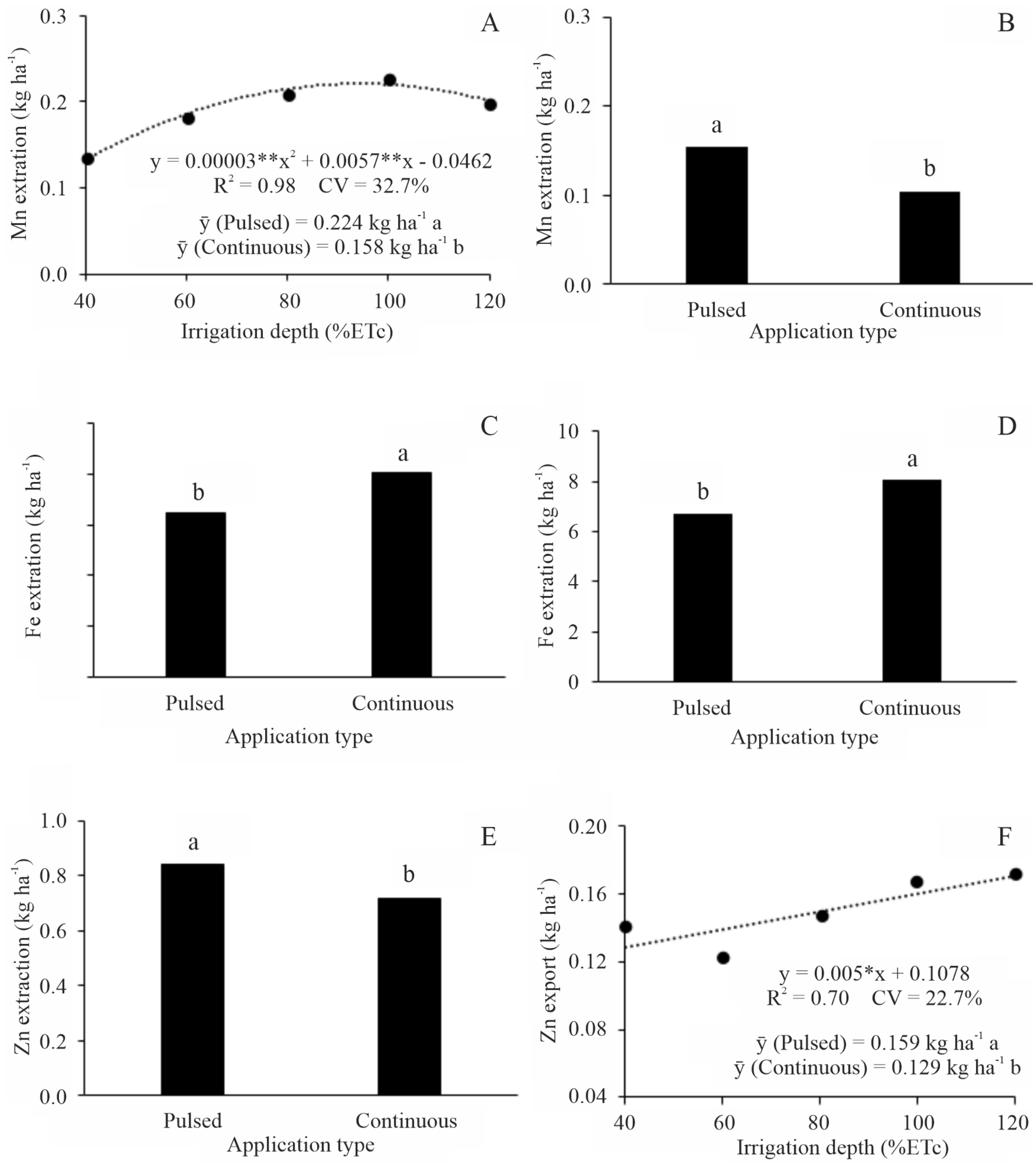
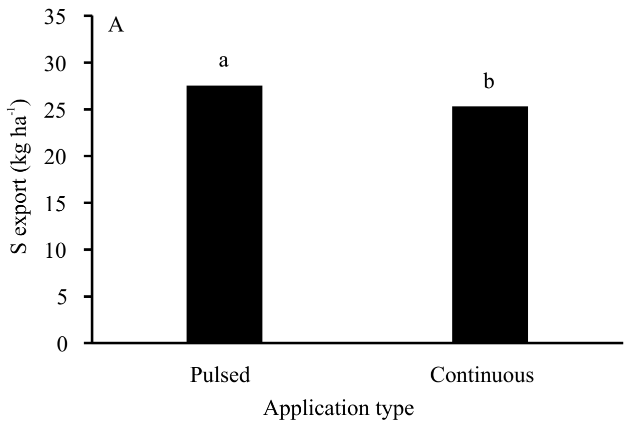


Figure 4. Extraction and export of manganese (A and B, respectively), iron (C and D, respectively), and zinc (E and F, respectively) in a sugarcane (*Saccharum officinarum*) crop as a function of replacement levels of crop evapotranspiration (Etc) and types of application (pulsed and continuous). Different letters indicate significant differences between the types of irrigation application (pulsed and continuous) by the Scott-Knott test. ** and *Significant at 0.01 and 0.05 probability, respectively.

sugarcane cultivated in a haplic Vertisol. For Lira et al. (2019), the export of S for sugarcane was 20 kg ha^{-1}.

Regarding Mg, the highest export was 30.37 kg ha^{-1}, obtained at 90.78% ETc (Figure 5 B), corresponding to an increase of 21.72% in relation to the value of 24.95 kg ha^{-1} at 40% ETc. Under irrigated management, Oliveira et al. (2011) found an export value of 99 kg ha^{-1} in sugarcane. According to Garcia et al. (2019), Mg is an important macronutrient for sugarcane cultivation because it acts directly on the concentration of sucrose in the stalks, a key factor for the quality of the crop.

When comparing nutrient accumulation, Salviano et al. (2017) observed the following order of nutrient export: K > N > S > Ca > P > Mg, with K and N being the most exported nutrients by the sugarcane crop. In the present study, the decreasing order of nutrient extraction and export by sugarcane differed depending on the type of irrigation application. Considering nutrient extraction, the decreasing order was: K > N > Ca > S > Mg > P > Fe > Zn > Mn > Cu for pulsed irrigation and K > N > S > Ca > Mg > P > Fe > Zn > Mn > Cu for continuous irrigation. Regarding nutrient export, the order was N > K > Ca > Mg > S > P > Fe > Zn > Mn > Cu for pulsed irrigation and N > K > Mg > Ca > S > P > Fe > Zn > Cu > Mn for continuous irrigation.



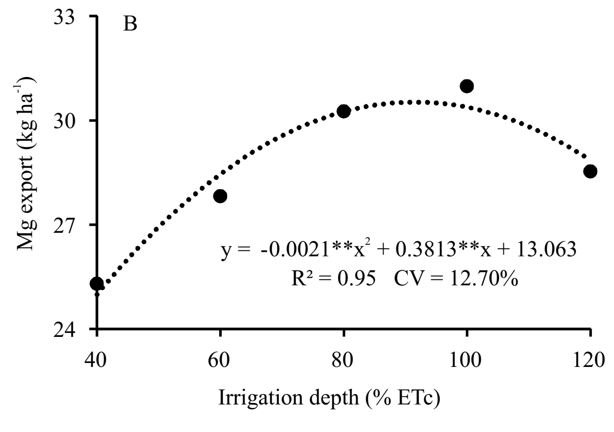


Figure 5. Export of sulfur as a function of irrigation application types (A) and of magnesium as a function of replacement levels of crop evapotranspiration (ETc) (B) in a sugarcane (*Saccharum officinarum*) crop. Different letters indicate significant differences between the types of irrigation application (pulsed and continuous) by the Scott-Knott test at 0.01 probability.

Conclusions

1. Pulsed irrigation favors a greater nutrient extraction and export by the sugarcane (*Saccharum officinarum*) crop, with irrigation blades between 90 and 100% of crop evapotranspiration resulting in a higher extraction and export of N, Ca, Mg, and Mn.
2. The decreasing order of nutrient extraction by sugarcane is K > N > Ca > S > Mg > P > Fe > Zn > Mn > Cu under pulsed irrigation and K > N > S > Ca > Mg > P > Fe > Zn > Mn > Cu under continuous irrigation.
3. The decreasing order of nutrient export by the crop is N > K > Ca > Mg > S > P > Fe > Zn > Mn > Cu under pulsed irrigation and N > K > Mg > Ca > S > P > Fe > Zn > Cu > Mn under continuous irrigation.

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Chief editor: Edemar Corazza
Edited by: Célia Tremacoldi

Data availability statement

Data available upon request: research data are only available upon reasonable request to the corresponding author.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.

Acknowledgments

To Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), for financing, in part, this study (Finance Code 001) and to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), for financial support (process number 423727/2018-4).