# Sulfur-improved manganese fertilization for sweet cassava under an overlimed organic management system

# Adubação de mandioca de mesa com manganês e enxofre sob um sistema de manejo orgânico com excesso de calcário

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**ABSTRACT**

The current farm management practices used to cultivate cassava, in a farm from Lago Oeste, Federal District, increased soil $pH_{water}$ value to 7.11, lowering Mn availability to plants, leading to low root yields. The soils were overfertilized and overlimed. The objective of this work was to evaluate Mn availability for cassava plants, as well as its yield under $MnSO_4$ and elemental sulfur ($S^0$) fertilization, in a high pH soil. An experiment was designed for evaluating $MnSO_4$ (0, 2.5, 5 and 10 kg Mn $ha^{-1}$) and $S^0$ (0 and 150 kg $S^0$ $ha^{-1}$) doses on cassava yield. The application of 150 kg $S^0$ $ha^{-1}$ increased cassava fresh root yield (25.7%), fresh shoot yield (17%), the number of roots (20%) and the starch percentage (7%), and decreased the cooking time (-13%), when compared with treatments without $S^0$. The application of 10 kg Mn $ha^{-1}$ increased the fresh root yield by 70% as compared to the control treatment. The highest yield was obtained when 10 kg Mn $ha^{-1}$ and 150 kg $S^0$ $ha^{-1}$ were applied, rendering 20.16 t fresh roots $ha^{-1}$, contrasting to the control, which produced 8.83 t $ha^{-1}$. The applied treatments were essential to increase cassava yield, however, were unable to provide adequate levels of Mn to plants.

**Keywords:** *Manihot esculenta* Crantz, organic agriculture, elemental sulfur, root yield.

**RESUMO**

As práticas de manejo para a cultura da mandioca em uma fazenda do Lago Oeste, Distrito Federal, elevaram o pH em água do solo a 7,11, diminuindo a disponibilidade de Mn para as plantas, as quais apresentaram baixa produtividade. O objetivo do trabalho foi avaliar a disponibilidade de Mn e a produção de mandioca sob a aplicação de $MnSO_4$ e enxofre elementar ($S^0$) em solo com pH elevado. Um experimento foi conduzido para se avaliar a adubação com doses de $MnSO_4$ (0, 2,5, 5 e 10 kg Mn $ha^{-1}$) e $S^0$ (0 e 150 kg $S^0$ $ha^{-1}$) localizada no sulco de plantio. A produtividade de raízes frescas aumentou com o aumento das doses de Mn e de $S^0$. A aplicação de 10 kg Mn $ha^{-1}$, com e sem $S^0$, aumentou em 70% a produção de raízes em relação ao tratamento testemunha, sem $MnSO_4$. A aplicação de 150 kg $S^0$ $ha^{-1}$ aumentou a produtividade de raízes (25,7%) e da parte aérea (17%), o número de raízes (20%), a percentagem de amido (7%), e diminuiu o tempo de cozimento (-13%), quando comparado aos tratamentos sem $S^0$. A produtividade mais elevada foi obtida quando 10 kg Mn $ha^{-1}$ e 150 kg $S^0$ $ha^{-1}$ foram aplicados, obtendo-se 20,16 t de raízes frescas $ha^{-1}$, contrastando com o tratamento controle, o qual produziu 8,83 t $ha^{-1}$. Os tratamentos aplicados foram essenciais para aumentar a produtividade de mandioca, entretanto, foram insuficientes para garantir o adequado suprimento de Mn para as plantas.

**Palavras-chave:** *Manihot esculenta* Crantz, agricultura orgânica, enxofre elementar, produtividade de raízes.

## 1 INTRODUCTION

Sweet cassava (*Manihot esculenta* Crantz.) crops grown in farms under organic management in the Federal District, Brazil, may exhibit manganese deficiency. This deficiency is characterized by the interveinal chlorosis of upper and middle leaves, causing low crop yield (Fialho et al. 2020, Marchi et al. 2021). The low availability of Mn is caused by the frequent and excessive use of soil amendments (usually excess of lime, poultry manure, and thermal phosphate fused with magnesium silicate and micronutrients, with alkalizing properties). Such practices have caused a substantial increase in soil pH. When soil $pH_{water}$ is above 6.5, normally it causes a decrease in soil levels of exchangeable $Mn^{2+}$ and readily reducible Mn and, consequently, there is a reduction in $Mn^{2+}$ uptake by plants (Reuter et al. 1988, Galrão 1999). The application of organic materials to the soil also contributes to the decrease in Mn availability, by Mn forming stable complexes with organic matter (Lopes 1998). Low manganese availability can be a serious limiting factor for plant growth, ultimately causing low crop productivity (Alejandro et al. 2020). Some sweet cassava genotypes grown in Federal District are very sensitive to low Mn availability (Fialho et al. 2020).

Seven cassava genotypes (IAC 576-70, known as "japonesinha"; BRS Moura; BRS 399; BRS 396; BRS 397; IAPAR 19, and Clone 450/08) were evaluated in two field experiments in the Federal District, grown in organically managed soils where $pH_{water}$ values were 7.07 and 6.27. Genotypes IAC 576-70 and BRS Moura were the most affected by the Mn deficiency in these experiments, showing an expressive interveinal chlorosis of young leaves. The Mn levels in soils of these two experiments, extracted by Mehlich-1, were both above 45 mg $dm^{-3}$ (Fialho et al. 2020). However, the manganese fertilization is not recommended for cassava crops grown in soils presenting values of Mehlich-1 extractable concentrations above 5.0 mg Mn $dm^{-3}$ (Galrão 1999, Lopes 1998, Souza et al. 2009), or DTPA extractable concentrations above 12 mg Mn $dm^{-3}$ (Lopes 1998). Despite the abundance of Mn in the soil, exceeding, by far, 5.0 mg Mn $dm^{-3}$, its availability to plants is highly constrained when soils $pH_{water}$ is above 6.5. Though, chemical methods used to estimate the Mn availability to plants, such as DTPA-TEA pH 7.3, HCl 0.1 mol $L^{-1}$, Mehlich-1 and 3, might not reveal the real Mn availability status for plants (Marchi et al.

2021). Soil tests do not appear to be able to predict the likelihood of limitations associated with Mn deficiencies or toxicities induced by pH and pE (Robson 1988) and, in addition, by root-induced changes in chemical and microbial properties in the rhizosphere (Marshner 1988). Such tests seem to be unable to account for the nature of the inorganic and organic reactions to which Mn is subject in soils (Hannam & Ohki 1988). In this case, a soluble source, such as manganese sulfate, and a strategy to increase the time that the dissolved Mn stays available to crops should be studied.

The application of banded 4.28 kg ha$^{-1}$ of Mn, alone, is non-responsive (Marchi et al. 2021). That study also showed that the combination of $MnSO_4$ application banded in soil along with elemental sulfur ($S^0$), or other methods, such as foliar application, and stem cuts treated with $MnSO_4$, improved Mn availability for plants. The authors showed important results related to the increase of cassava yield in high pH soils. According to Marchi et al. (2021), more research must be developed to overcome the Mn deficiency in cassava cultivated in high pH soils, specially using higher $S^0$ fertilization doses than the previously studied. The use of acidifying supplements, such as $S^0$, may increase Mn availability in the soil. The oxidizing reaction of $S^0$ acidifies the soil and improves availability of the soil Mn in a cheap and simple treatment for cassava, as well as crops in general, under Mn deficiency (Reuter et al. 1988).

A study was conducted in an organically managed soil with high pH soil located in the Northwestern region of the Federal District, Brazil. The soil presented low Mn availability and was treated with increasing Mn doses and $S^0$ fertilization aiming to increase cassava crop yield.

## 2 MATERIAL AND METHODS

This study was carried out in a farm in Lago Oeste, Federal District, Brazil (15º40´39" S and 48º09´89" W; 1232 m a.s.l.). This farm has been under organic management since 2007. The climate is tropical savanna (AW), according to Köppen classification. The soil was classified as Typic Acrustox (USDA 2015); Latossolo Vermelho Amarelo ácrico, according to the Brazilian classification system (Santos et al. 2018). The soil analysis (0-20 cm) presented the following characteristics (Embrapa 2017): $pH_{water}$ = 7.11; extracted by Mehlich-1 (HCl 0.05 mol L$^{-1}$ + $H_2SO_4$ 0.05 mol L$^{-1}$; 1:10 soil:solution ratio): P = 109.6 mg dm$^{-3}$ and K = 120.6 mg dm$^{-3}$; S extracted by $Ca(H_2PO_4)$ 0.01 mol L$^{-1}$ (1:2,5) = 12.8 mg dm$^{-3}$; by KCl (1 mol L$^{-1}$): Ca = 5.4 cmol$_c$ dm$^{-3}$, Mg = 2.0 cmol$_c$ dm$^{-3}$ and Al < 0.1 cmol$_c$ dm$^{-3}$; micronutrients extracted by Mehlich-1: Cu

= 1.2 mg dm$^{-3}$, Zn = 50.5 mg dm$^{-3}$, and Mn = 27.5 mg dm$^{-3}$; B (hot water) = 2.1 mg dm$^{-3}$; sand = 333 g kg$^{-1}$; silt = 280 g kg$^{-1}$; clay = 387 g kg$^{-1}$; Organic matter = 39.1 mg g$^{-1}$. The area was previously fertilized and cultivated with green vegetables. A composite sample, from an area 20 m away from the experiment, under native Cerrado vegetation, was collected as a reference of the soil before conversion to agriculture. The objective of the reference sample was to compare the changes the soil was submitted to, after amended and fertilized, for years, under the current practices of the farm. The reference soil, analyzed using the same methods described above, presented the following characteristics: pH$_{water}$ = 5.17; P = 0.5 mg dm$^{-3}$; K = 19.0 mg dm$^{-3}$; Ca = 1.1 cmol$_c$ dm$^{-3}$, Mg = 0.6 cmol$_c$ dm$^{-3}$; Al = 0.3 cmol$_c$ dm$^{-3}$; Cu = 0.7 mg dm$^{-3}$; Zn = 0.4 mg dm$^{-3}$; Mn = 4.2 mg dm$^{-3}$; B = 0.5 mg dm$^{-3}$; sand = 330 g kg$^{-1}$; silt = 276 g kg$^{-1}$; clay = 388 g kg$^{-1}$; organic matter = 41.8 g kg$^{-1}$.

The design of the experiment was a 4 X 2 factorial with randomized blocks and four replications. Plots consisted of 4 rows with 7 plants each, spaced 1.2 x 0.8 m (26.88 m$^2$). Treatments consisted of four rates of Mn (as MnSO$_4$.H$_2$O) as follows: 0.0, 2.5, 5.0, and 10.0 kg Mn ha$^{-1}$, combined with two rates of elemental sulfur (S$^0$): 0 and 150 kg ha$^{-1}$. The products were banded in the rows before planting, mixed with the soil. After the treatments were applied, there were no supplementary fertilizers added to the area.

The sweet cassava (*Manihot esculenta* Crantz) cultivar IAC 576-70, known as "Japonesinha" was selected for its excellent culinary properties (Fialho et al. 2009), and for showing severe interveinal chlorosis in leaves and low yield when under Mn deficiency stress in prior experiments (Fialho et al. 2020, Marchi et al. 2021).

Cassava cuttings were planted on January 12$^{th}$, 2015. In the fourth month after the emergence of plants, the fourth expanded leaf of all plants from the 10 central plants in each plot was collected (Ribeiro et al. 1999). Leaves from each plot were dried in an oven at 60 ºC for 72 h. Macro (P, K, Ca, Mg, and S) and micronutrients (Fe, Cu, Mn, and Zn) were extracted by HNO$_3$:HClO$_4$ in a digestion block (Bataglia et al. 1983) and analyzed by inductively coupled plasma - optical emission spectrometry (ICP-OES). For the determination of the N content in roots, stems, and leaves, 0.1 g samples of dried and ground plant tissue were digested in sulfuric acid. Thereafter, the N content was measured in a semi-micro Kjeldahl apparatus (Malavolta et al. 1997).

At the harvest time, on December 11th, 2015, the following growth data were recorded: plant height, first branch height, fresh shoots yield, fresh roots yield, number of roots, starch percentage in roots by the hydrostatic weight scale (Grosmann & Freitas 1950) and cooking time (Alves et al. 2005). Leaves, stem, and roots were harvested from the six plants within the central portion of each plot. The fresh weight of the collected material was recorded. A sample of each collected material (leaves, stem + branches, and roots) was weighed before (*in loco*) and after drying in an oven at 60 ºC until constant weight. Dried samples were milled and analyzed for nutrient contents as previously described for leaves. Tests for normality (Shapiro & Wilk 1965) and equal variance (O'Neill & Mathews 2000) were used prior to the analysis of variance. The data were submitted to the analysis of variance using the F test ($p < 0.05$) and, when the means were statistically different, the Tukey test was applied.

After plants were harvested, soil samples were collected from each plot. Each sample was composed by five sub-samples, forming a "W" shape, collected in interrow positions within the central portion of the plot. The soil was not collected where the $S^0$ and $MnSO_4$ bands were applied, as fertilization bands were narrow (about 15 cm) and the sub-samples could, by chance, be collected outside $S^0$ and $MnSO_4$ bands.  Soil analyses for the macro and micronutrients, as well as organic matter and $pH_{water}$, were performed following Embrapa (2017). A Pearson's correlation analysis to relate the data from the soil and plant chemical analysis was performed using the Sigma Plot 14.5 software (Sigma Plot Software; San Jose, California, USA).

The Principal Component Analysis (PCA), with standardized scores, was conducted on nutrient offtake data. The PCA was performed with FactoMineR and factoExtra in R software (3.4.0) using the data of all 32 plots to identify the variable with higher weight in the linear combination of the first two main components.
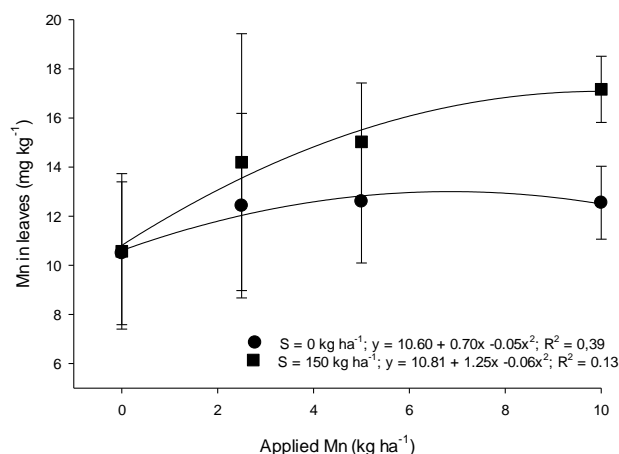
**3 RESULTS AND DISCUSSION**

The application of both Mn and $S^0$ increased the concentration of Mn in leaves collected in the fourth month after emergence from 10.5 to 17.3 mg kg$^{-1}$ (Figure 1). Although there were increases in Mn concentrations in leaves in the fourth month in treated plots, the values were below 30 mg kg$^{-1}$, therefore, rated as "very deficient" (Howeler 2002). The concentration of other nutrients in leaves, nitrogen and, in a smaller extent, sulfur, were also found below the adequate range (Table 1). Despite that, plants did not show any visual symptoms of N or S deficiency.

Although there is recommendation for the application of N in cassava (Raij et al., 2007), it is also not usual to add N to the organic cassava crops during its growth, especially when it is cultivated after a fertilized crop (maize). Excess nitrogen usually promotes vegetative growth of cassava, while decreasing root yield (Fialho & Vieira 2011).

Figure 1. Manganese concentration in leaves collected at the fourth month.



S = 0 kg ha$^{-1}$; y = 10.60 + 0.70x -0.05x$^2$; R$^2$ = 0,39
S = 150 kg ha$^{-1}$; y = 10.81 + 1.25x -0.06x$^2$; R$^2$ = 0.13

Source: original material from authors

Table 1. Mean plant nutrients concentration in youngest fully expanded leaf blades of cassava collected at the fourth month and adequate concentration of nutrients according to several authors. [*]

|  | Fe | Cu | Zn | Ca | Mg | P | N | K | S |
|---|---|---|---|---|---|---|---|---|---|
|  | --- mg kg$^{-1}$ --- | | | ---------------------------- g kg$^{-1}$---------------------------- | | | | | |
| Means | 244.0 | 7.0 | 86.8 | 23.1 | 3.2 | 3.1 | 30.0 | 21.7 | 2.7 |
| s[**] | 39.2 | 3.2 | 22.9 | 1.8 | 0.4 | 0.6 | 13.2 | 3.4 | 0.6 |
| References | Adequate concentration | | | | | | | | |
| (Howeler 2002) | 120–140 | 6–10 | 35–57 | 5–7.2 | 2.4–2.9 | 3.8–5 | 51–58 | 14.2–18.8 | 3.0–3.6 |
| (Ribeiro et al. 1999) | 120–140 | 6–10 | 30–60 | 7.5–8.5 | 2.9–3.1 | 3–5 | 51–58 | 13–20 | 2.6–3 |
| (Raij et al. 1997) | 60–200 | 5–25 | 35–100 | 5–15 | 2–5 | 2–5 | 45–60 | 10–20 | 3–4 |

[*]There were no significant statistical differences among treatments; n = 32. [**] Standard deviation.
Source: original material from authors

Moreover, concentrations of nutrients in leaves, collected at the fourth month showed that Ca, Mg, K, Fe, and Zn (Table 1) were higher than the adequate. These concentrations may reflect, probably, a concentrating effect in plants, as plants did not grow properly due to lower availability of Mn, and, probably, of N and S. Even though, high concentrations of these nutrients in soil could lead to a higher concentration of nutrients in leaves.

At the harvest time, soil samples were collected from experimental plots (Table 2), in interrows. Soil chemical attributes, such as Ca, Mg, S, K, Mn, Zn, and Fe, as well as organic

matter content and $pH_{water}$, were analyzed. Soil pH, among plots, at the end of the experiment, ranged from 6.64 to 7.32 (mean = 7.06; std dev = 0.17, n = 32). The results were statistically homogeneous, and there were no differences between the initial and final interrow soil conditions.

Table 2. Mean macronutrients and micronutrients concentration in soil samples collected at the end of the experiment (averages of all treatments).

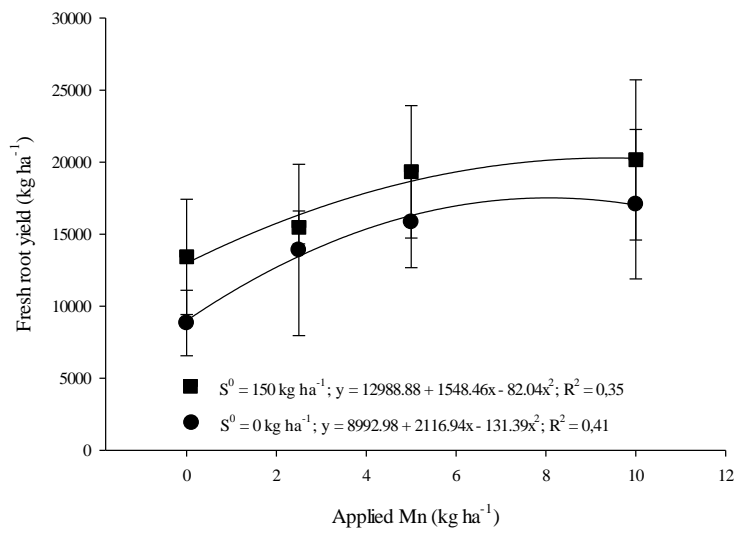| | Ca | Mg | S | K | P | $pH_{water}$ | O.M. | Mn | Cu | Zn | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | - $cmol_c\ dm^{-3}$ - | | ----- $mg\ dm^{-3}$----- | | | | $g\ kg^{-1}$ | ----- $mg\ dm^{-3}$----- | | | |
| Means* | 5.2 | 2.0 | 13.1 | 120.6 | 109.6 | 7.06 | 39 | 29.6 | 1.3 | 50.3 | 34.5 |
| $s$** | 0.3 | 0.1 | 2.0 | 34.4 | 24.3 | 0.17 | 2 | 3.4 | 0.3 | 4.7 | 4.1 |

* n = 32. ** Standard deviation.
Source: original material from authors

Soil concentration of available Ca and Mg in the samples collected in the interrows were 5.4, and 2.0 $cmol_c\ dm^{-3}$, respectively (Table 2). In addition to the high soil pH, these high concentrations of Ca and Mg may have contributed to the decrease in uptake rate of $Mn^{2+}$ (Marshner 1988). Values of available Ca higher than 3.8 $cmol_c\ dm^{-3}$, and Ca + Mg above 5.2 $cmol_c\ dm^{-3}$ are known to decrease Mn absorption by cassava (Santos & Tupinambá 1982). In fact, in many crops, not only excess of available Ca, Mg, in soil, but also Zn, Fe, and K, in excess, may cause Mn deficiency in plants (Marshner 1988, Lopes 1998).

The effects of Mn and, probably, S deficiencies, were attenuated when the rates of the applied Mn and S° were raised. Thus, with the addition of Mn and S fertilizers, cassava root yield presented a significant increase (Figure 2). The mean fresh root yield increased 70% with the application of 10 kg $ha^{-1}$ Mn (from 10,990 to 18,600 kg $ha^{-1}$). The mean fresh root yield also increased by 25.7% (from 13.8 to 17.3 t $ha^{-1}$) with the application of $S^0$.

Figure 2. Fresh roots yield of cassava as a function of rates of S0 and Mn.



$S^0 = 150$ kg ha$^{-1}$; y = 12988.88 + 1548.46x - 82.04x$^2$; R$^2$ = 0,35

$S^0 = 0$ kg ha$^{-1}$; y = 8992.98 + 2116.94x - 131.39x$^2$; R$^2$ = 0,41

Source: original material from authors

The highest root yield was obtained when 10 kg Mn ha$^{-1}$ and 150 kg S$^0$ ha$^{-1}$ were applied, producing 20.16 t fresh roots ha$^{-1}$, contrasting to the absolute control treatment, which produced 8.83 t ha$^{-1}$. The increase in production is likely an increase in S availability, as well as a direct effect of S$^0$ oxidation lowering the soil pH (locally, on cassava rows), increasing the availability of manganese to the cassava crop. The benefits of S$^0$ application in soils with high pH, increasing Mn availability, were shown for other crops, such as corn and beet (Reuter et al. 1988).

Although significant yield gains were detected in the Mn fertilized treatments, the Mn deficiency was widespread over the whole experiment, as noticed by the observation of Mn deficiency symptoms (interveinal chlorosis) and leaf Mn concentrations below adequate range. Therefore, the root yield in the experiment was probably affected by Mn deficiency. Root yield was lower than that found in trials with the same cultivar, in farms located at Federal District and vicinity (Unai, Minas Gerais state; Fialho et al. 2009, Vieira et al. 2015). Even though, in different environmental conditions, including duration of growth, location, type of soil, etc, is not appropriate to compare crop yields, these authors found, in an average of five experiments, under conventional management system, root yields ranging from 28.67 to 55.93 t ha$^{-1}$, with a mean value of 37.05 t ha$^{-1}$. The lowest yield obtained by those authors was 42% higher than the maximum yield obtained in the present experiment. It shows that the Mn deficiency was not completely overcome, and other environmental factors, including N deficiency, decreased the cassava yield during the experiment.

Even though, in the present experiment, by applying 150 kg $S^0$ $ha^{-1}$ in cassava rows, the crop was benefitted, increasing its production significantly. Not only the fresh root yield increased (Figure 2) as compared with the control, but the increase was also noticed in fresh shoot yield (17%), the number of roots (20%), starch percentage (7%), and a decrease in the cooking time (13%; Table 3). The effects of the S in the crop may be related to the increase in the availability of S and Mn to the crop, along with other micronutrients whose availability may be related to the decrease in soil pH, such as Fe, Cu and Zn.

Table 3. Means of the number of roots per plant, starch content, and cooking time, evaluated in eight treatments with Mn and $S^0$ rates for cassava grown in an organic management system farm.

| Treatments | Fresh shoot yield | Number of roots | Starch | Cooking time |
|---|---|---|---|---|
| kg $S^0$ $ha^{-1}$ | kg $ha^{-1}$ | - | % | - |
| 150 | 19466 a | 7,81 a | 28,21 a | 18'04" b |
| $s**$ | 3618 | 1.3 | 2.3 | 2.12 |
| 0 | 16569 b | 6,50 b | 26,21 b | 20'45" a |
| $s$ | 3338 | 1.7 | 3.2 | 4.0 |

*Means followed by different letters in columns are statistically different ($p<0.05$) by the Tukey test. ** Standard deviation.

Source: original material from authors

Cooking time in the present experiment (Table 3) was lower than those showed by Fialho et al. (2009) for the same cultivar (IAC 576-70) in three experiments in the Federal District (22 to 27 minutes), and by Vieira et al. (2015) in Unai, Minas Gerais state (22 minutes). The quality of the cassava is directly related to the cooking time, thus, the lower the cooking time, the better is the food quality. There are scarce, if any, studies on the influence of fertilizer on root starch characteristics of cassava (as starch is an emerging major industrial raw material; Omondi 2020). The lower availability of N, in the present experiment, may have contributed for an increased starch percentage, decreasing the cooking time. However, it is difficult to compare results in different experiments, as pointed before, mainly when evaluation methods differ. Therefore, sticking to the results, the $S^0$, in the present experiment, improved the quality of the cassava, by decreasing its cooking time.

The Principal Component Analysis (PCA; Figure 3) shows, on the dimension 2, an alignment with Mn in leaves collected in the fourth month with concentrations of P, Mg and Mn in the soil. Although the soil analyzed in the interrow was not impacted by the decrease in pH by $S^0$ oxidation, the covariation implies that P, as well as available Cu and Zn, play an important role for the plant nutrition, increasing Mn absorption. On the dimension 1, the PCA expresses

those nutrients which impacted the most on the plant's growth (roots, shoots, and starch yield), including the whole set of macronutrients, and Cu and Zn, which are micronutrients whose availability is mostly affected by soil pH (Figures 3 and 4). Manganese concentration in cassava plants showed the highest direct correlation ($r=0.69$; $p<0.001$) with the starch percentage, which shows, for the experimental conditions, the importance of Mn application on the nutritional and industrial quality of the crop. Other nutrients, such as Cu, Zn, Fe, Mg and K showed also high correlation values ($r>0.6$) with starch percentage. The nutrients which were the most correlated ($r>0.8$) with roots and shoots were P, Mg, K, Zn, and Cu. Although these nutrients (P, Mg, K, Zn, and Cu ) are important for cassava nutrition, and its addition to the soil may back a better Mn absorption by the plant, the correlations shown with them may have reflected the effect of S as a treatment that promoted an increase in their availability (Figure 4). In addition, the lack of S fertilization was found to have a strong yield limiting effect in the synthesis and accumulation of starch in cassava roots (Alame et al. 2022).

Figure 3. Principal component analysis (PCA) plot showing the multivariate variation among fresh root yield, fresh shoot yield; soil chemical attributes: Mg_soil, _P_soil, Cu_soil, Zn_soil and Mn_soil; Mn in leaves collected at the fourth month (Mn_4months); and N, Ca, Mg, K, S, P, Zn, Cu, and Mn in leaves collected at the harvest. Vectors indicate the direction and strength of each variable to the overall distribution. The first two principal axes explained 69.13% of the variance ($\lambda 1 = 9.3$ and $\lambda 2 = 3.1$).
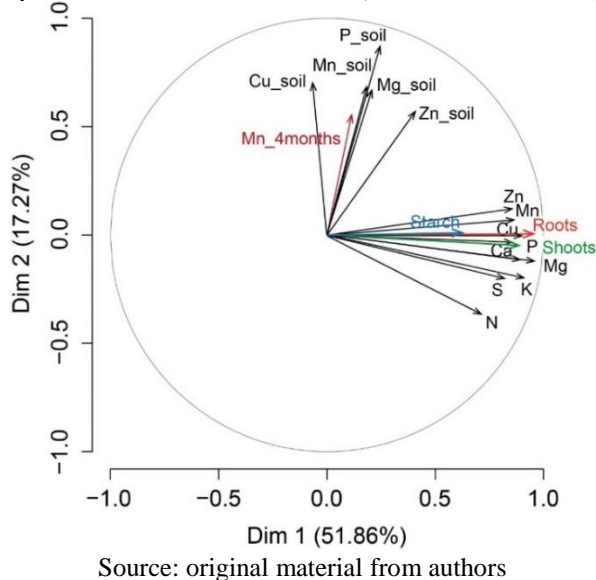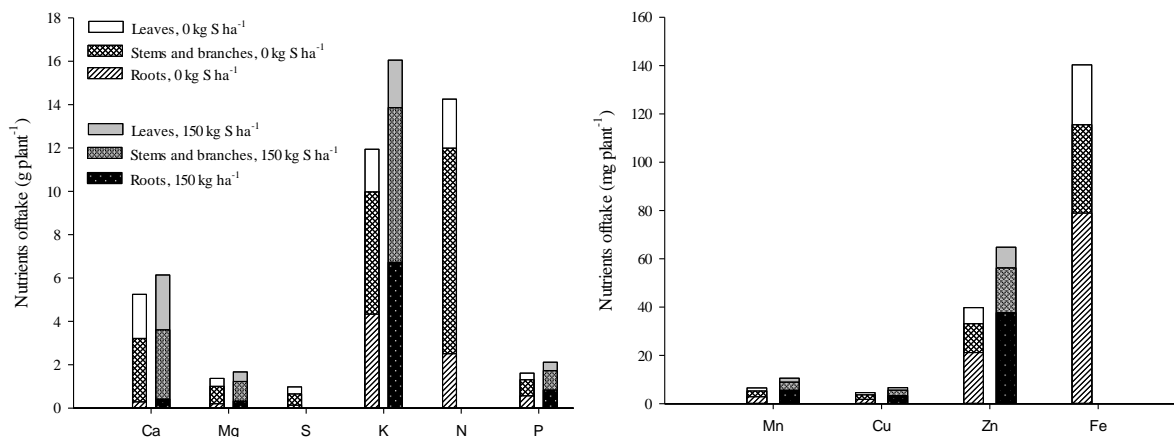


Source: original material from authors

Figure 4. Cassava macro and micronutrients offtake. Grouped bars (0 and 150 kg S ha-1), for Ca, Mg, K, P, Mn, Cu and Zn, are significantly different by the Tukey test (p<0.05); single bars, for S, N and Fe, were not significantly different among treatments, therefore, are means of all Mn and S0 rates (n = 32, for roots, stems + branches, and leaves).

Source: original material from authors

The nutrients offtake by the cassava crop showed that there was a significant increase in P, K, Mg, Ca, Zn, Cu and Mn extracted by those plants treated with 150 kg $S^0$ ha (Figure 4). Although S is required in lesser amounts compared to other macronutrients, it is essential for many functions in plants, i.e., the formation of chlorophyll and plant proteins (Janket et al., 2021). Sulfur also was found to increase the uptake of macronutrients, namely, nitrogen, phosphorus, and potassium (Salvagiotti et al. 2009). Therefore, there was also a synergic effect on the absorption o S, applied as $S^0$ and as $MnSO_4$, with the nutrients depicted above.

Soil supply of Mn, therefore, is a complex variable that depends not only on soil chemistry but also on plant responses as well as activity of microorganisms (Rengel 2015). Manganese presents a slow abiotic oxidation rate (Nealson et al. 1988, Norvell 1988), therefore, in soils with high pH values, the application $MnSO_4$, banded in rows, may become available for a limited time to plant uptake, improving plant growth, and suplying the soil with $SO_4^{2-}$. Soil acidifiers, by its turn, such as $S^0$, improve availability of Mn.

Both soluble Mn source and $S^0$ were positive for the cassava growth. The manipulation of soil pH by using $S^0$ banded in rows improved cassava yields. Even though, attempts to overcome defficiencies in cassava, mainly of Mn, in the present experiment, were not completely solved. Therefore, other supplementary management practices should be studied. To solve the defficiency of Mn in high pH soils for cassava, some proceedings could be implemented in the

future are: the use of higher concentrations of Mn banded in rows than in the present experiment (e.g. 20 to 40 kg ha$^{-1}$, Reuter et al. 1988, Mascagni & Cox 1985), stem cutting treatment before planting (Marchi et al. 2021, Howeler 2002), foliar methods of Mn application, and the use of acidic fertilizers.

## 4 CONCLUSIONS

1.    The treatments S$^0$ and Mn rates were essential to increase cassava (cultivar IAC 576-70) yield in the soil under organic management system.

2.    Culinary properties were improved, by increasing the starch percentage, and shortening the cooking time.

3.    The applied treatments were unable to overcome completely the Mn deficiency.

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