Soil application of sulfur in the production of chocolate habanero pepper (*Capsicum chinense* Jacq.)

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ABSTRACT
Objective: The cultivation of chocolate with habanero chili was established to determine the effect of the application of agricultural sulfur on its production.
Design/methodology/approach: The experiment was conducted from August to July, under field conditions and plastic mulch in Apatzingán, Michoacán, Mexico. Treatments consisted of wettable agricultural sulfur applied at doses of 15, 30, 45 and 60 kg ha^{-1}, plus a control without sulfur application. The sulfur was incorporated into the soil around the plants 10 days after transplanting.
Results: The number of fruits per plant was significantly lower in the control treatment compared to the 15 and 45 kg ha^{-1} of sulfur doses. Similarly, fruit length and diameter were smaller in the control treatment compared to all sulfur doses. No significant differences in fruit weight were observed between the control and the sulfur treatments. The highest fruit yields were achieved with sulfur doses of 15, 30, and 45 kg ha^{-1}, yielding 22.5, 20.6, and 22 t ha^{-1}, respectively.
Limitations on study/implications: Sulfur fertilization constitutes an effective strategy to increase yields under the experimental conditions.
Findings/conclusions: Applying 15 kg ha^{-1} of sulfur is sufficient to enhance fruit production in chocolate-type habanero peppers grown in alkaline soils.

Keywords: fruit diameter, fruit number, fruit yield.

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INTRODUCTION

From the Solanaceae family, the genus *Capsicum* is the most economically important, encompassing approximately 30 species. Its fruits have been used for about 7,000 years BC, initially as part of the diet of native Mexicans (Govindarajan, 1985; Dong *et al.*, 2014). Among the most significant species is the habanero chili (*Capsicum chinense* Jacq.), recognized as one of the chilies with the highest capsaicin content, reaching up to 131.8 μm g^{-1} of dry fruit (Duelund and Mouritsen, 2017). In Mexico, 30,056 tons were produced

in 2023, representing a value of 670 million pesos (MXN) (SIAP, 2024). Approximately 80% of habanero chili production is marketed as fresh fruit, while the rest is used for the production of sauces, pastes, and dehydrated products (FIRCO, 2017). There is significant diversity in fruit colors, primarily orange, red, purple, yellow, and chocolate (López-Espinosa *et al*., 2018). The latter is mainly produced in Michoacán and is highly valued for its pleasant flavor. However, the yield in this region is 6.05 t ha^{-1}, which is below the national average of 18.64 t ha^{-1} (SIAP, 2024).

An alternative to increasing agricultural crop yields is proper nutrition, which, under soil cultivation conditions, primarily relies on the supply of nitrogen, phosphorus, and potassium. Sulfur is the fourth or fifth most required macronutrient for plants; however, fertilization with this nutrient is not commonly recommended for crops grown in soil (Barros-Milhomens *et al.*, 2020). Sulfur in plant nutrition enhances the availability of phosphorus (P), potassium (K), zinc (Zn), manganese (Mn), and copper (Cu); it reduces soil pH and promotes the conversion of unavailable P into plant-available P. Sulfur is also required for the synthesis of essential amino acids such as cysteine and methionine (Hunde, 2020). Additionally, it is necessary for chlorophyll formation, which plays a critical role in physiological functions related to energy production (Aula *et al.*, 2019; Narayan *et al.*, 2023). Moreover, sulfur strengthens plant defenses against pest attacks, nutrient stress, and high temperatures (Hunde, 2020).

A significant effect has been demonstrated in increasing yield and improving the quality of agricultural crops such as onion (*Allium cepa* var. *cepa*), barley (*Hordeum sativa* var. *nutans*), and cabbage (*Brassica oleraceae* var. *capitata alba*) with the application of sulfur at doses ranging from 40 to 80 kg ha^{-1} (Skwierawska *et al.*, 2008). Although in crops such as grasses, the response increases as the sulfur dose is raised up to 50 kg ha^{-1}, higher amounts result in yield reduction due to antagonistic effects (Aula *et al.*, 2019). In contrast, in other crops such as potato (*Solanum tuberosum* L.), even when grown in soils with very low sulfur levels, no response was observed to the addition of this element at doses of 10 and 20 kg ha^{-1} (Giletto *et al.*, 2012). For this reason, it is essential to determine the response of each crop, as well as the most appropriate sulfur dose. In chocolate-type habanero chili, studies on this topic are scarce. Therefore, the objective of this study was to evaluate the effect of agricultural sulfur application on fresh fruit yield and yield components, as well as to identify the optimal sulfur dose for maximizing fruit yield in chocolate-type habanero chili.

MATERIALS AND METHODS

Study Area

The study was conducted at the experimental field of the Faculty of Agricultural Sciences of the Michoacan University of San Nicolás de Hidalgo in Apatzingán, Michoacán, located at the coordinates 19° 04’ 56” N and −102° 22’ 15” W, at an altitude of 325 meters above sea level. The climate is classified as BSh’g, corresponding to a very hot semi-arid steppe climate (García, 2004). During the crop cycle, maximum temperatures ranged from 37 to 43 °C, minimum temperatures ranged from 13 to 20 °C, and the total accumulated rainfall was 710.2 mm. These data were provided by the Department of Surface Waters and River Engineering, Hydrometeorology Unit of Apatzingán, whose agrometeorological station is located at the study site.

Seedling Establishment and Crop Management

The research was conducted from August to July, beginning with the sowing of seedlings in 242-cell polystyrene trays, which were previously disinfected by immersion in a solution of water with sodium hypochlorite at a dose of 5 mL L^{-1}, and then washed with water to remove the chlorine. Subsequently, the trays were filled with peat moss, and one chocolate-type habanero chili seed was placed in each cavity. The trays were placed under shade netting. Irrigation was provided daily in the morning according to the crop's water needs. Prior to transplanting, the soil was prepared with a plowing, followed by a harrowing and furrowing at 80 cm between rows. The irrigation system was then installed using plastic drip tape and agricultural mulch 1.20 m wide, Calibre 90, silver/black color. Transplanting was done 40 days after sowing, with one plant placed every 40 cm, resulting in a density of 31,250 plants per hectare.

Prior to the establishment of the crop, at a depth of 0-30 cm, the soil was classified as loam with a slightly alkaline pH (7.8), medium levels of inorganic nitrogen (21.7 mg kg^{-1}) and phosphorus (18.6 mg kg^{-1}), high in potassium (976 mg kg^{-1}), high in calcium (5454 mg kg^{-1}), high in magnesium (1854 mg kg^{-1}), medium in sulfur (9.2 mg kg^{-1}), cation exchange capacity (CEC) of 45 cmol kg^{-1}, and an apparent density of 1.13 t m^{-3}; according to the Mexican Official Standard NOM-021-SEMARNAT-2000 (DOF, 2002). The fertilization provided during the crop's production cycle was 130-120-160 kg ha^{-1} of N, P_2O_5, and K_2O. The fertilizers used to supply the nutrients were: Urea (45% N), Potassium nitrate (13% N - 44% K_2O), and Monoammonium phosphate (12% N - 61% P_2O_5). The fertilizers were applied through a fertigation system. Irrigation was provided according to the crop's water needs, ensuring that the crop was always maintained at field capacity.

Treatments and Experimental Design

The treatments consisted of the application of 93% agricultural wettable sulfur at doses of 15, 30, 45, and 60 kg ha^{-1}, compared to a control without application. The treatments were applied as a base fertilizer, 10 days after transplanting, buried around the plant. The experimental design was a randomized complete block design, with each treatment repeated four times, resulting in 20 experimental units. Each experimental unit consisted of three rows, each 3 meters long. For the useful plot, five plants from the central part of the middle row were selected.

Response Variables

Several fruit harvests were made as they reached harvest maturity (coffee-colored fruits). The harvest started 120 days after transplanting and spanned a six-month period. In each harvest, five fruits were randomly selected per experimental unit, and their equatorial diameter (cm) and length (cm) were measured using a caliper. The total number of harvested fruits was counted, and their weight was recorded using a digital scale to determine the number of fruits per plant and the average fruit weight. The fruit yield per hectare was estimated as follows:

$$\textit{Yield}\ (\text{t ha}^{-1}) = (\textit{number of plants per hectare}) \times (\textit{fruit weight per plant})$$

Statistical Analysis

The response variable data were analyzed using the SAS statistical package, version 9.4 (SAS, 2017). Variables that showed statistically significant differences were subjected to Tukey's mean comparison test ($p \leq 0.05$).

RESULTS AND DISCUSSION

The application of sulfur at all evaluated doses favored an increase in the number of fruits per plant, as well as the length and diameter of the fruits. With the application of 15 and 45 kg ha^{-1} of sulfur, the habanero pepper plants showed the highest number of fruits per plant, with increases of 57.2% and 47.5%, respectively, compared to the control plants. Regarding fruit length and diameter, these were similar across all sulfur doses and statistically higher than those of the control. The plants with sulfur had fruits with lengths 22 to 36% greater than those from plants without sulfur application, and diameters 45 to 63% larger than those from plants without the nutrient. Similar fruit weight was observed between the control plants and the four sulfur doses (Table 1).

The higher number of fruits per plant with sulfur application can be attributed to this element, as it favors the fruit setting percentage and, consequently, the number of fruits per plant in *C. annum* (Kumari *et al.*, 2017). This, along with the increase in fruit length and diameter, resulted in a significant increase in fruit yield in the plants with sulfur application in the present study. The highest increases were recorded with the doses of 15, 30, and 45 kg ha^{-1} of sulfur (Figure 1).

The positive response to sulfur application in the habanero chili crop can be attributed to the fact that it is an essential element in plant nutrition, important for chlorophyll

Table 1. Tukey's mean comparison test of the evaluated variables in chocolate habanero pepper.

Sulfur doses kg ha^{-1}	Number of fruits per plant	Fruit length (cm)	Fruit diameter (cm)	Average weight of fruits (g)
0 (Control)	110.9 b[¶]	2.36 b	1.79 b	4.38 a
15	174.3 a	2.89 a	2.82 a	4.14 a
30	142.8 ab	3.20 a	2.91 a	4.60 a
45	163.6 a	2.93 a	2.59 a	4.32 a
60	138.6 ab	3.01 a	2.87 a	4.19 a
General Mean	146.0	2.88	2.59	4.32
Prob. de F	**	**	**	NS
$DMSH_{0.05}$	41.2	0.50	0.52	0.75
CV%	12.53	7.69	8.93	7.71

[¶]Means with the same letters within the same column do not differ statistically from each other (Tukey, $p \leq 0.05$). **$p \leq 0.01$; NS=not significant. $DMSH_{0.05}$=honest minimum significant difference. CV=coefficient of variation.

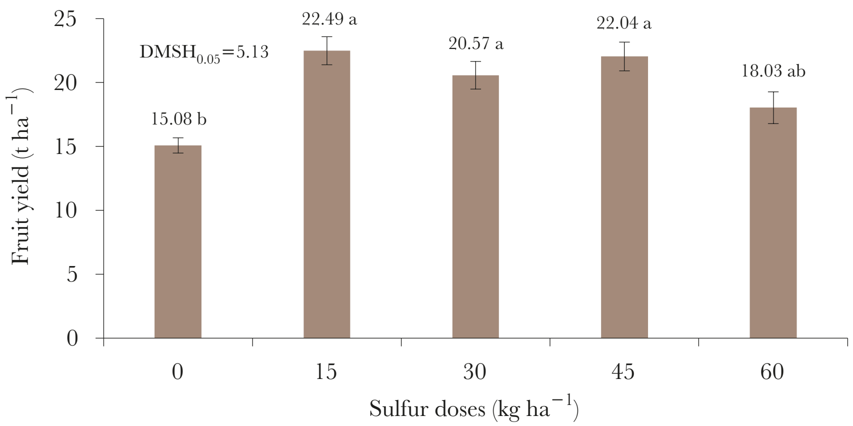

Figure 1. Habanero chili fruit yield as a function of sulfur dose. DMSH$_{0.05}$=honest significant minimum difference.

formation, secondary metabolites, and necessary for physiological functions, growth, and plant development. Additionally, there are proteins containing Fe-S groups that are necessary for multiple biological processes, such as photosynthesis, energy generation, photoprotection, and metabolism (Aula *et al.*, 2019; Narayan *et al.*, 2023). Sulfur is also an element that, at appropriate levels in the plant, reduces damage caused by oxidative stress and high temperatures, such as those occurring during the growth cycle of the crop, which, on some days, reached 43 °C. In relation to its interaction with other nutrients, it has been found that sulfur increases the absorption of N, P, and K, which can improve the supply and enhance plant nutrition (Aula *et al.*, 2019; Narayan *et al.*, 2023).

It has been found that the application of sulfur increases crop yield as the application rate increases, when the sulfur content in the soil is low or medium and the pH is very acidic or alkaline. However, most crops show a decrease in yield at doses equal to or greater than 50 kg ha^{-1} (Oliveira *et al.*, 2017; Nascente *et al.*, 2017), which may explain why habanero chili in our study showed a slight reduction in fruit yield at doses higher than 45 kg ha^{-1} of sulfur (Aula *et al.*, 2019).

In the production site, according to the physical and chemical analysis, the soil has a medium sulfur content (9.2 mg kg^{-1}), so the addition of this element favored the production of habanero chili fruit. These results are similar to those found in *C. annum* L. variety LCA-334, where the application of S at doses of 7.5, 12.5, 15, 20, and 25 kg ha^{-1} significantly increased the fresh chili yield, with the dose of 7.5 kg ha^{-1} showing the highest yield increase, which was 65.8% compared to the control treatment with no application (Kumari *et al.*, 2017).

Similarly, in wheat (*Triticum aestivum* L.) cultivation, with an initial sulfur content of 110.2 mg kg^{-1} in the soil, the application of 40 kg ha^{-1} of sulfur increased the grain yield by 27 and 22%, a result attributed to the stimulatory effect on chloroplast protein synthesis, which leads to greater photosynthetic efficiency, favoring agricultural yield (Singh *et al.*, 2014).

The addition of sulfur to soils with medium sulfur levels does not guarantee improved productive responses in crops, as occurred in potato (*Solanum tuberosum* L.) cultivation with the supply of sulfur at doses of 10 and 20 kg ha^{-1}, which did not increase tuber yield (Giletto *et al.*, 2012). Similarly, no improvement was observed in canola with increasing doses of sulfur up to 60 kg ha^{-1} as ammonium sulfate (Kaefer *et al.*, 2014). Therefore, the variation in the agricultural yield response to sulfur supply and the most appropriate dose, which differs for each crop, indicates variability in the requirements between plants (Narayan *et al.*, 2023). In the present study, where improvements in production were recorded with the addition of sulfur at doses of 15, 30, and 45 kg ha^{-1}, habanero chili yields exceeded the national average of 18.64 t ha^{-1} (SIAP, 2024). Therefore, sulfur supply as a fertilizer is a viable option that enhances the yield of this crop under the given production conditions, with 15 kg ha^{-1} of sulfur being sufficient to boost production, as it results in the highest increments. Although higher doses do not reduce yield (they remain stable), they can reduce profitability due to the cost of a larger amount of sulfur.

CONCLUSIONS

The application of agricultural sulfur as a base fertilizer affects the production and fruit dimensions of habanero chili. To obtain a higher number of fruits per plant, fruits with greater length and diameter, as well as higher yield per hectare, the most appropriate dose is 15 kg ha^{-1} of wettable sulfur.

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