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Red and Brown Soils Increase the Development and Content of Nutrients in Habanero Pepper Subjected to Irrigation Water with High Electrical Conductivity

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***Abstract*. The characteristics of the soil in the Peninsula of Yucatán confer unique organoleptic properties to the habanero pepper (*Capsicum chinense* Jacq.), and thus this entity possesses the denomination of origin of the species, making these chilis the most coveted, nationally and internationally. However, the extreme microtopographic variation distinguishing the Peninsula complicates the transfer of technologies and the successful establishment of agricultural practices. Maya farmers of the region identify the brown soils as preferable for the cultivation of this chili, although there is some controversy among the farmers regarding the best yields when the quality of the water used for irrigation is poor. No studies of the effect of soil type on this plant have been carried out. This work evaluated the impact of three types of soil of the Peninsula (red, brown, and black) on growth, fruit production, and nutrient content in soils and plants, during different phenological stages. The results indicate that the red and brown soils were the best for the growth and production of the fruit. In the black soil, it was possible to observe greater retention and accumulation of sodium applied in the water used for irrigation and in the macronutrients N, P, K, which may have led to a negative effect in the development of the fruit in these plants. Moreover, the plants growing in red and brown soils seem to make a more efficient use of the nutrients, presenting higher values of N, P, and K in their tissues in the flowering-fructification stage. These results are particularly useful in the realization of agricultural plans with a lower consumption of fertilizers, which allows an increase in yield, particularly if we take into account the enormous problems of saline intrusion worldwide and in this region.**

Leptosols are the most common soils in the world (12%). In México the percentage is 24%, and in the State of Yucatán it is 80% (INEGI, 1998). Yucatán has an extension of 39,524 km^2, within which the physiography has no elevated areas, presenting only a rocky plain that has developed over a deep sequence of Cenozoic limestone layers. Sinkholes, dry blind valleys, mounds 1 to 2 m high, and rocky outcrops can also be observed (Bautista-Zúñiga et al., 2003). The area designated to agriculture occupies only 794,145 ha. This fact is primarily due to the large diversity of soils in small extensions of land, which does not allow good agronomic management (Borges-Gómez et al., 2014). According to Duch (1988), although the soils of Yucatán have the same parental material, this heterogeneity is due to their different time of development. Similarly, Escamilla et al. (2005) reported the existence of "patches" of soil of different sizes, instead of homogenous extensions of hectares.

The Yucatán soils are shallow, with colors ranging from red to black with various tones of brown, and an abundant content of stones and outcrops of calcareous shell (Borges-Gómez et al., 2005). Various approaches are used to describe the spatial heterogeneity of the soils in this region, such as the Mayan nomenclature of the soils, which is based on the characteristics, for example the geographical relief, soil color, stoniness, rockiness, and depth (Bautista et al., 2005).

Bautista et al. (2005) identified three types of soil found in the depressions inside the microrelief of the region. Two of these types were red: the K'ankab (10 to 50 cm of depth) and the Hay lu'um (less than 10 cm of depth). A third type, Chaltún, which varies in color from red to black, with combinations of reddish brown, can also be found in the mounds. Similarly, these authors identified three classes of soils in the mounds, all of which were black: the Box lu'um, which presents stones 5 to 10 cm in diameter; the Ch'och'ol, with finer soil in comparison with the Box lu'um; and the Tsek'el, with very little fine soil. In the work of Bautista et al. (2005), the Chich lu'um soil, which contains an abundance of gravel, is also mentioned, along with the Chak lu'um, a deep red soil, although they were not found in the area under study.

Estrada-Medina et al. (2013) reported that the farmers of the locality of Hocaba, situated in the central region of the state of Yucatán, can identify 11 different soil types in the region, differentiated by topographic position, color, quantity of rocky outcrops, rock fragments, and their water retention capacity. Estrada Medina et al. (2013) reported that the red soils (K'ankab and Chaklu'um) were found only on the plain, and these soils were characterized by the presence of very few rocky fragments, good water retention, a higher content of clay, and a lower quantity of organic material; whereas the black soils (Box lu'um and other varieties), which are found in the mound, present stones and rocky outcrops. Most of these soils have poor water retention, a lower content of clay, and a high content of organic material. The Chichlu'um soil was one of the variants of black soil, despite its light brown color. It is found on the flat tops of the mounds and presents good water retention.

It has been suggested that the red coloring of the soils on the plains is a result of the formation of hematite produced by the oxidation of the iron, due to the aerobic conditions of the same, resulting from a rapid percolation of the water (Bautista-Zúñiga et al., 2003); whereas the black coloring of the mound soils would be a result of the high retention of organic material (Chesworth, 2008).

Moreover, these soils can vary in the composition of exchangeable cations due to the quantity and type of clays present, among other factors (Tinker and Nye, 2000). They also present a structure of communities

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comprising different microorganisms, a fact that could have an effect not only on plant production, but also on the protection of drinking water and carbon sequestration (Estrada-Medina et al., 2016).

Habanero pepper (*Capsicum chinense* Jacq.) is one of the most important horticultural species cultivated in the Peninsula of Yucatán. This chili, one of the hottest in the world, belongs to the *Capsicum* genus; and besides being appreciated for its taste and pungency, it is also rich in vitamins, minerals, and nutrients. Although it is not Mexican in origin, the agro-climatic conditions of the Peninsula led to the development of creole species with outstanding organoleptic characteristics, for which it obtained the denomination of origin "Habanero pepper of the Peninsula of Yucatán" in the year 2010 (Diario Oficial de la Federación, 2010). According to the official Mexican norm (NOM-189-SCFI-2012), the organoleptic characteristics (taste, aroma, and pungency) of the habanero pepper of the Yucatán Peninsula distinguish it from those cultivated in other producing regions, due to the climate and soil conditions of the region.

The Peninsula exports ≈4500 tons of habanero pepper each year to countries such as the United States, Japan, Brazil, Canada, South Korea, and Germany. This quantity is insufficient because the international demand is around 7000 tons per year. The soil of the region is a determining factor in the quality of these chilis, but also in the low agricultural yield obtained in the Peninsula. Thus it is necessary to identify the factors influencing this parameter to design agricultural strategies that facilitate an increase in these yields, while conserving their organoleptic quality.

Borges-Gómez et al. (2014) carried out the physical and chemical characterization of 24 soils of 17 municipalities in the Yucatán where habanero pepper is cultivated, reporting that these soils were highly heterogeneous. For example, they found that more than 50% of the soils were thin, stony, with rapid surface drainage; while 42% were of medium depth, with a lower percentage of stone. All the soils presented a low apparent density and high porosity; while the contents of organic material, N, P, K, and other elements were variables among the different types of soil.

According to Estrada-Medina et al. (2013), the farmers of the central part of Yucatán prefer the brown soil for the cultivation of local peppers—their reasoning being simply that the pepper grows well in this type of soil. One reason could be nutritional; however, for the moment, this factor remains unknown. There is also some controversy among the farmers regarding how to obtain the best yields when the irrigation (rain) is poor. Some farmers believe that the best option is the soil type of the mounds, while others prefer the soil of the plain (Estrada-Medina et al., 2013). Further studies are needed to clarify the impact of the soil type on the growth and development of the habanero pepper to design better strategies for the cultivation in accordance with the soil type, including the management of chemical fertilizers. Once this clarification is achieved, it will be possible to reduce the present contamination of underground water, resulting from the excessive use of chemical fertilizers (Pérez-Ceballos and Pacheco-Ávila, 2004) and to increase agricultural yields.

The aim of this work was to determine the effect of three types of soil contrasting in color: red soil (Chaklu'um), brown soil (Chichlu'um), and black soil (Boxlu'um) on the growth and production of habanero pepper fruits and on the nutrient content in the soils and plants.

Materials and Methods

Plant growth conditions. The experiment was conducted between the months of July and Oct. of 2017. Plantlets of habanero pepper (*Capsicum chinense* Jacq. 'Jaguar') with ≈48 d of germination were used. These were transplanted to polyethylene bags containing 12 kg of three different types of Yucatecan soil, under nonsterile conditions: the red soil (RS, Chaklu'um), the brown soil (BRS, Chichlu'um) and the black soil (BLS, Box lu'um).

The bags were placed in a Baticenital greenhouse located in Sierra Papacal (CIATEJ, Unidad Sureste), with a north–south orientation, a ridge height of 7.0 m, with a triple-layer plastic cover (25% shade), and lateral walls of high-density plastic antitrips screens.

Water from a local well was used for irrigation, the electric conductivity of which oscillated between 2.8 and 3.4 mS. For the fertilization, the technological package of Soria et al. (2002) was employed, which is recommended for habanero pepper cultivated in the soils of Yucatán. It follows the formula of 120N–100P–150K kg·ha^{-1}. The fertilizer used was the triple 18, and the 18N–46P–00P (Ultrasol) was applied in the irrigation water twice weekly after the 10 posttransplant days (PTD). The micronutrients were applied on the leaves with one weekly application of the commercial product Bayfolan Forte. At 20 PTD, before floral initiation, a growth regulator containing gibberellin, cytokinin, and auxin (Biozyme$^{®}{}_{TF}$, Arysta LifeScience) was applied. Irrigation was applied sporadically (about twice a week) during the first 15 d after the transplant; subsequently, the irrigation frequency was maintained at 2 L per bag, every third day.

Analysis of growth and fruit production. Plants growing in the three types of soil were collected at 21, 35, 55, and 100 PTD. To carry out the analysis of the aerial part, this part was cut at the base of the stem and was weighed (fresh aerial weight). It was then placed immediately in bags at –80 °C.

For the root analysis, the soil was carefully removed and sieved to recover the finest roots. Subsequently, the whole root system was collected and weighed. The root was also placed in bags and stored at –80 °C.

To determine the dry weight, both parts were lyophilized and weighed (aerial and root dry weight). The total number of fruits per plant and the total weight of these fruits were evaluated in the plants of 100 PTD. These fruits were grouped according to size in five categories (in cm: <1, 1–2, 2–3, 3–4, and >4), and the number of fruits per category was determined. For all the analyses, five plants from each type of soil were used per time. An ANOVA was carried out, and the means were compared with a Tukey's analysis ($P \leq 0.05$).

Chemical analysis of the soils and the plant tissue. The soils from the five bags of each kind of soil were mixed, grouped together, and dried in an oven. A representative sample of 1 kg of each soil was used for the physico-chemical analysis of the same. The lyophilized tissue of the root and leaves from the five plants per sample and soil type were grouped and mixed for use in the chemical analyses.

The physico-chemical analyses of the soil and plant tissue were conducted by NUTRELAB. The parameters measured for soil were pH and electrical conductivity (EC) (potentiometer); % of organic carbon and organic material (OM) (Walkley and Black method); N (Kjeldahl, this was determined by the steam distillation process); phosphorus (extracted by the Olsen method and quantified by colorimetry); the exchangeable cations Ca, Mg, K, and Na (with ammonium acetate and quantified by atomic absorption); micronutrients such as Fe, Mn, Cu, and Zn (extractable with DTPA and quantified by atomic absorption); B (extractable with hot water and quantified by azomethine-H); the cation exchange capacity (CEC, with ammonium acetate); apparent density (AD) (test tube method), texture (method of Boyoucos); field capacity (FC); and point of permanent wilting (gravimetric method). For the plant samples, N (Kjeldahl), phosphorous (molibdato-vanadato), and Ca, Mg, K (atomic absorption) were determined. All evaluations were repeated three times. The results were compared using Tukey's adjusted test for multiple comparisons ($P \leq 0.05$), after an ANOVA of one-way (Proc GLM version 9.1; SAS Institute, Cary, NC) was conducted.

Results

Plant growth analysis. At 21 PTD, no significant differences were observed in the fresh weight of aerial parts among the plants growing in the three soils (Fig. 1A). During this time, the highest increment values were obtained in this parameter, equivalent to an increase about eight times greater in comparison with those presented by the plants at the moment of transplantation. This growth corresponds to an increment rate of ≈0.4 g·d^{-1}. In contrast, the fresh root weight on this day was higher and this was also observed among the plants growing in the red and brown soils in comparison with those in the black soil (Fig. 1B). The lowest values of aerial and root dry weight were observed for the plants of the black soil, although these were not statistically different from those of the red soil on this day (Fig. 1C and D).

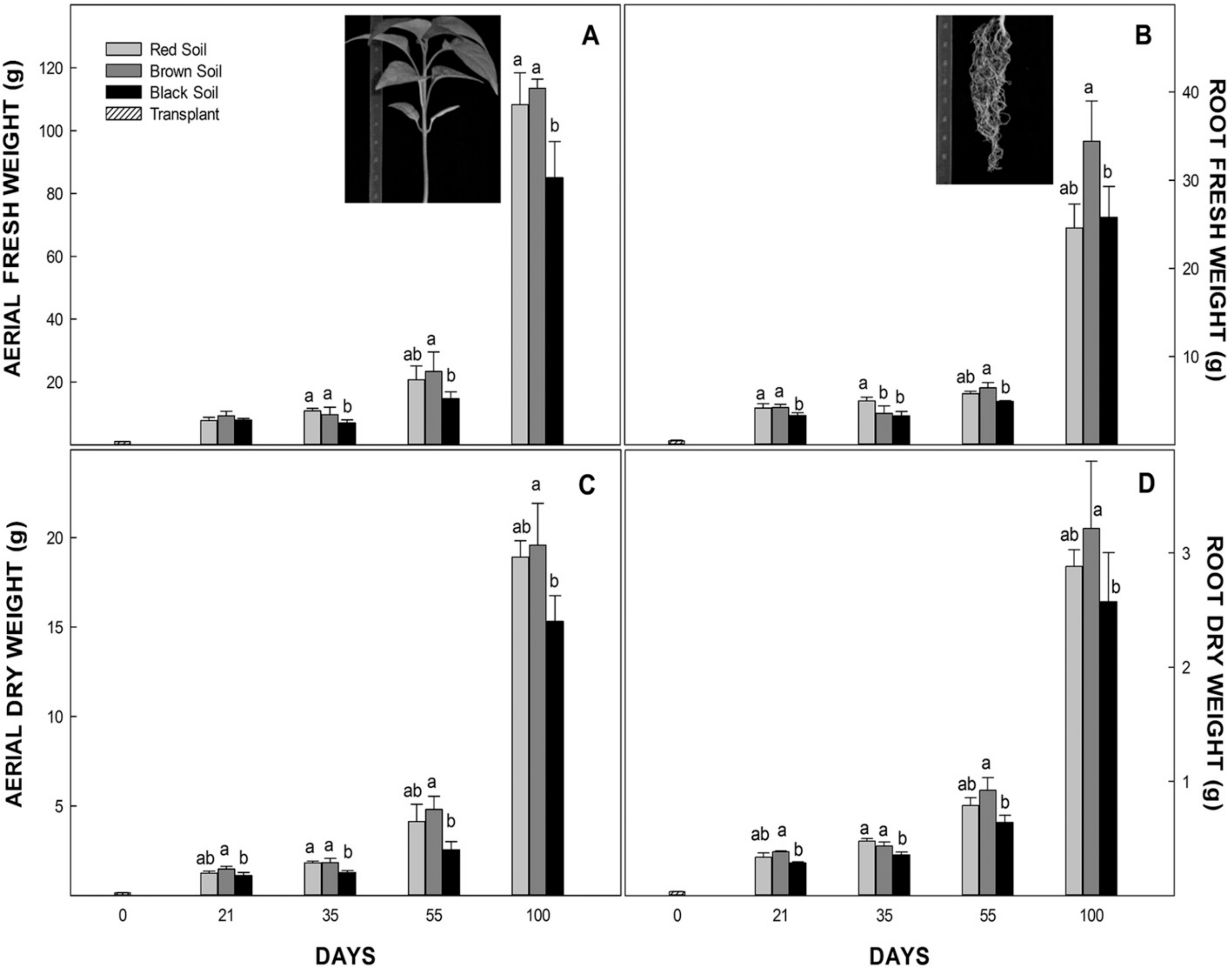

Fig. 1. Dynamic of growth response in habanero pepper cultivated in three types of soils. The fresh weight (**A**, **B**) and dry weight (**C**, **D**) of the aerial part (**A**, **C**) and root (**B**, **D**) of the plants cultivated for 100 d in red, brown, and black soils were evaluated. The values represent the average of five plants, and the bars are the standard deviation. Different letters indicate significant differences among the soils in the same day, according to the Tukey's test ($P \leq 0.05$).

From 21 to 35 PTD, the rate of plant growth was lower in comparison with that of the first 21 d. The increase in aerial fresh weight was 1.4, 1.04, and 0.9 times for the plants in the red, brown, and black soils, respectively. At that moment, no significant differences were found in the values of fresh and dry aerial weight and dry root weight between the plants growing in red and brown soils, with both presenting higher values in comparison with those of the plants in the black soil (Fig. 1A–C). It is important to note that the plants growing in the black soil had lost some leaves, which could have affected the aerial weight. However, the fresh root weight was highest in the plants of the red soil, followed by those of the brown soil, and last, the plants growing in the black soil (Fig. 1B). From the transplantation to the present moment, this parameter had increased ≈11, 8, and 7 times in the plants originating from the red, brown, and black soils, respectively. Moreover, as was expected, at 35 PTD, all the plants presented flower buds.

At 55 PTD, the fresh and dry weights of both the aerial part and the root were significantly greater in the plants growing in the brown soil, in comparison with those of the black soil; while those of the red soil presented no statistical differences with the other two soils (Fig. 1). At this moment, the plants were in the full flowering stage and the initiation of fructification.

The results at 100 PTD were similar with those previously mentioned, except for the aerial fresh weight, which was higher for the red soil, the same for the brown, and lower for the black soil (Fig. 1A).

Fruit development and production. The total number of fruits per plant was evaluated in the plants at 100 PTD. Keeping in mind that at 35 to 40 PTD, flowering began; this timing means that at 65 d, the plants would be presenting fruits in different stages of development, from small to mature. All fruits larger than 0.2 cm present in the plants were quantified and weighed. The total number of fruits was not significantly different among the plants growing in the different soil types at 100 PTD (Fig. 2A). However, the fresh weight of the fruit was practically double in the plants originating from the red soil, in comparison with those of the black soil (Fig. 2B), suggesting that the fruits of these plants are better developed.

To investigate this aspect, the fruits were divided into five categories according to their length (<1, 1–2, 2–3, 3–4, and >4 cm), and the number and total weight of the fruits in each category were quantified. According to the analysis of soil type, the plants of the red soil presented the largest quantity of fruits in the ranges between 2 to 3 and 3 to 4 cm, and the rest of the fruits were distributed in a similar manner among the rest of the ranges. In the case of the fruits obtained from the plants growing in the brown soil, the highest number of fruit was presented in the range from 2 to 3 cm, and the lowest number in the extreme ranges. In the plants cultivated in the black soil, the highest numbers of fruits were distributed in the ranges of <1 cm and 2 to 3 cm, and the lowest quantity occurred in the fruits with a longitude greater than 4 cm

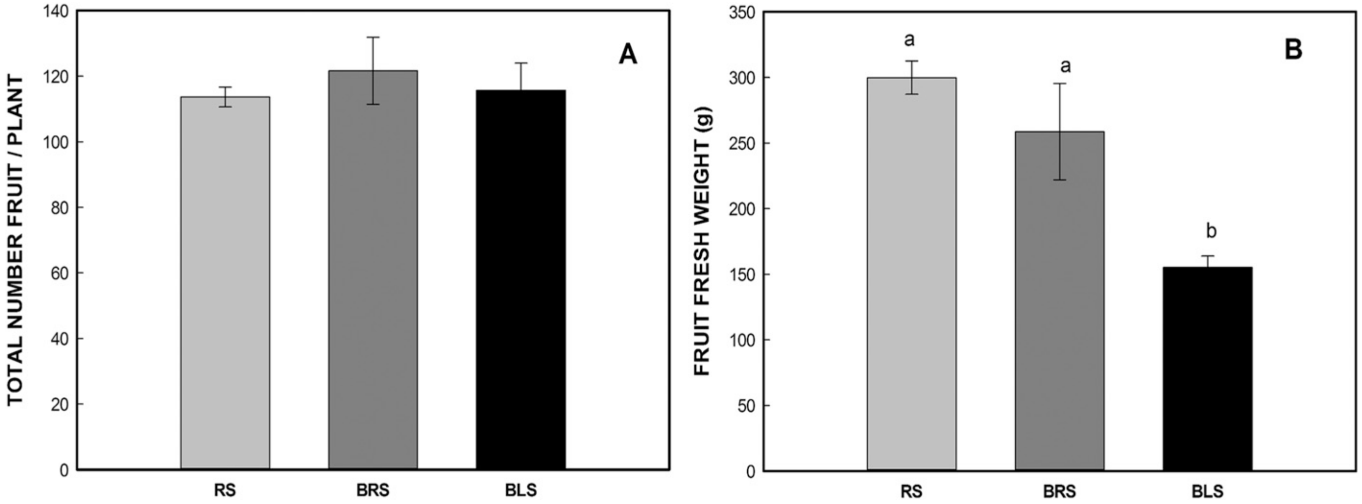

Fig. 2. Effect of soil type on the production (**A**) and fresh weight of the fruits (**B**). Total number of fruits and total fresh weight of the fruits was evaluated in habanero pepper plants at 100 d after transplantation, growing in the three types of soil. The vertical lines represent the standard deviation (n = 5). Different letters indicate significant differences between the soils according to the Tukey's test ($P \leq 0.05$).

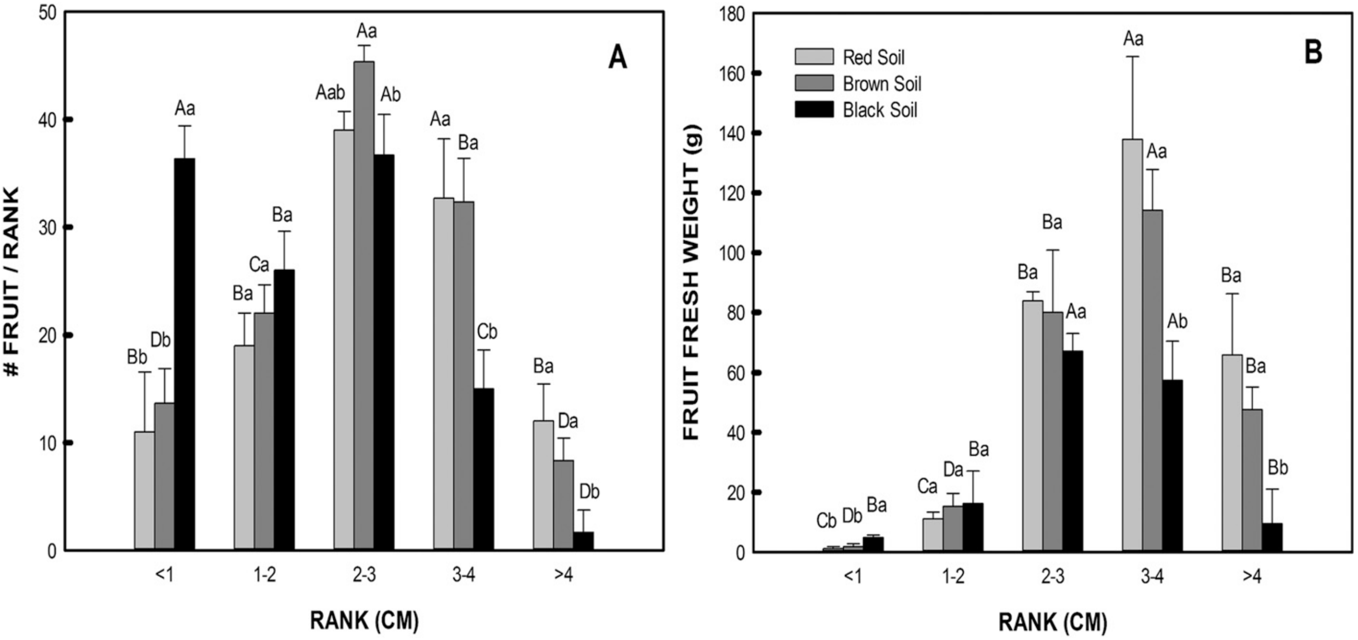

Fig. 3. Development of the habanero pepper fruits, according to soil type. The fruits from habanero pepper plants cultivated over a period of 100 d in three types of soils were divided into five ranges (<1, 1–2, 2–3, 3–4, and >4 cm). The number (**A**) and the total weight of the fruits (**B**) in each range were quantified by size. The data represents the average of five plants. Different capital letters indicate significant differences among the ranges in the same type of soil, according to the Tukey's test ($P \leq 0.05$). Different small letters indicate significant among the soil types in the same range in accordance with the Tukey's test ($P \leq 0.05$).

(Fig. 3A). The analysis by ranges clearly shows that no significant differences were found in the number of fruits in each range between the plants of the red and brown soils, and that these values were lower than those found for the plants of the black soil in the range below 1 cm, and higher in the ranges of 3 to 4 cm and above 4 cm (Fig. 3A).

In other words, the plants from the black soil presented a greater number of small, poorly developed fruits, very few of which were able to reach the expected size for this date, which was above 3 cm (Figs. 3 and 4).

The total weight of fruits per range was significantly higher for the fruits of the two higher ranges in the plants of the red and brown soils, in comparison with the black soil, with the opposite occurring in the smaller fruits (Fig. 3B). The average weight of the fruits between 2 to 3 cm was 2.15, 1.76, and 1.83 g for the plants of the red, brown, and black soils, respectively; and for the fruits between 3 to 4 cm, it was 4.22, 3.53, and 3.82 g, respectively. For the small fruits (<1 cm) and the largest (>4 cm), the average weight was similar for all the plants at ≈0.12 and 5.55 g, respectively.

Significantly, it was observed that the change in color of the fruit, from green to orange, indicating the ripening, occurred in fruits larger than 2 cm in the plants of the red and brown soils. However, this process was observed in fruits of the smallest ranges originating from the plants of the black soil, indicating that the fruits ripened before reaching an adequate degree of development (Fig. 4).

Initial physico-chemical characterization of the soils. It is known that soils of different colors have different physico-chemical properties that contribute precisely to these color changes. In the initial characterization of the soils, before the transplantation of the plants, the three types of soil did not differ in the pH, which was neutral with values of ≈7.3 to 7.4.

Fig. 4. The type of soil gave rise to modifications in the growth and ripening of the habanero pepper fruits The photographs show a representative image (n = 5) of the total number of fruits per plant for the plants growing in the red (**A**), brown (**B**), and black (**C**) soils.

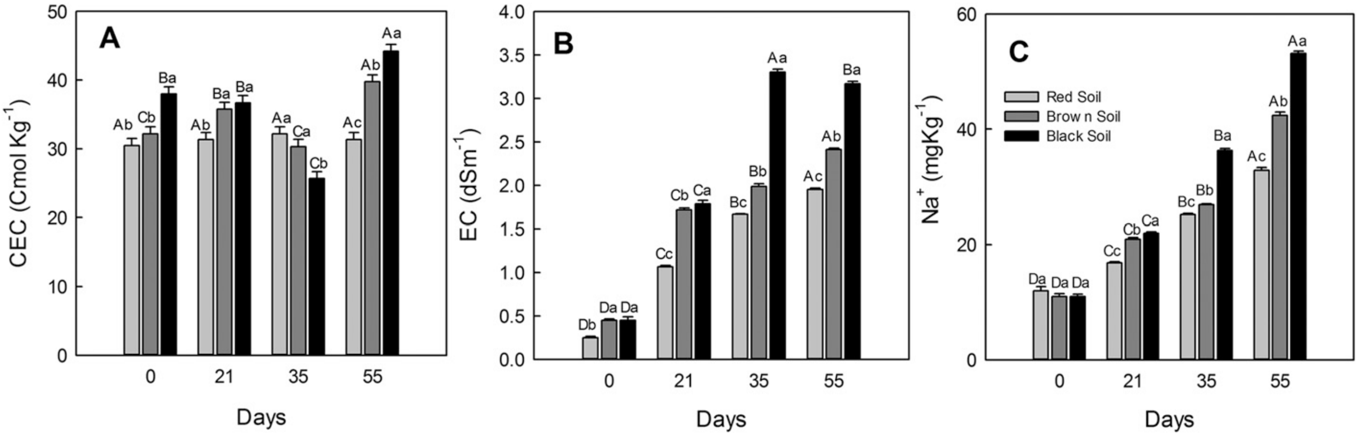

Fig. 5. Changes in the cation exchange capacity (CEC) (**A**), electrical conductivity (EC) of the soils (**B**), and Na content (**C**) of the same during the growth of the habanero pepper plants. The values are the average of three repetitions; different capital letters indicate significant differences among days in the same type of soil (Tukey's test, $P < 0.05$). Different small letters indicate significant differences among soil types in the same range, according to the Tukeýs test ($P \leq 0.05$).

The EC and the percentages of C and OM were greater and equal in the brown and black soils, respectively, in comparison with the red soil (Figs. 5 and 6).

The red soil is clay loam with a medium texture (43% / 30% / 26% of sand / clays / silts, respectively), while the brown soils (49% / 25% / 25% of sand / clays / silts, respectively) and the black (61% / 21% / 17% of sand / clays / silts, respectively) are loamy sand. The CEC was lower for red and brown soils, and the highest was that of the black soil (Fig. 5A). A contrasting behavior was observed for the FC, with values of 50.3, 46.6, and 48.7% for the red, brown, and black soils, respectively; and for the permanent wilting point, 32, 29, and 31%, respectively.

Regarding the chemical composition, the most important differences among the soils were observed in the P, where the black soil presented the highest values (10.1 mg·kg^{-1}), followed by the brown soil (6.8 mg·kg^{-1}), and lastly the red (3.4 mg·kg^{-1}). The Fe$^{+2\ +\ 3}$ fluctuated between 4 mg·kg^{-1} (red and brown soils) at 5.7 mg·kg^{-1} (black soil), while the Mn^{+2} was 3.9 mg·kg^{-1} for the red soil and 5 mg·kg^{-1} for the brown and black soils. The content Cu^{+2} was similar for all the soils (2 mg·kg^{-1}), as was that of Na (11 at 13 mg·kg^{-1}).

Physicochemical changes of the soils during plant development. It has been reported that an efficient absorption of nutrient, which allows an adequate growth and accumulation of nutrients in the leaves during the initial stages of growth, is important for a good result in the posterior stages of flowering and fructification. Given the effect of soil type on the production of fruits in the plants, our aim was to register some of the physico-chemical changes in the soils during the plant growth stage (21 PTD) up to the initiation of the flowering-fructification stages (35 and 55 DPT).

The pH of the soils was not modified until 55 PTD, remaining in values between 7.6 and 7.8. The AD of the red soil diminished significantly at 21 PTD (0.95 ± 0.01 t·m^{-3}), and subsequently recovered up to values similar with those presented at the beginning of the experiment (1.07 ± 0.01 t·m^{-3}). This value was significantly higher than those presented by the other soils at 55 PTD. In the brown soil, a slight reduction can be observed at 35 PDT (0.88 ± 0.01 t·m^{-3}), remaining in the initial values during the subsequent evaluations (1.01 ± 0.01 t·m^{-3}), and occupying an intermediate position with respect to the other two soils. In contrast, for the black soil, this parameter diminished significantly (0.95 ± 0.01 t·m^{-3}) until reaching the lowest at 55 DPT (0.77 ± 0.005 t·m^{-3}).

The CEC of the soils at 21 PTD remained at values similar with those of the initiation, before the transplantation; and this was lower for the red soil, in comparison with the other two soils. The red soil did not modify its CEC throughout the sampling; but it was interesting to note that, at 35 PTD, this parameter diminished by 15% and 30% for the brown and black soils, respectively. At this point (which coincided with the initiation of the flowering stage), the black soil presented the lowest values, reaching 25.7 cmol·kg^{-1}. However, at 55 PTD, the brown and black soils modified their CEC once again, but this time reaching 30% and 70%, respectively, in comparison with those presented at 35 DPT. At this stage, the black soil presented the highest value of CEC (44.20 cmol·kg^{-1}), followed by the brown soil (39.8 cmol·kg^{-1}), and the lowest values corresponded to the red soil (31.3 cmol·kg^{-1}) (Fig. 5A).

The EC was always higher in the black soil, followed by the brown, and last, the red (Fig. 5B). These values increased during the period evaluated, reaching the highest values at 35 PTD for the black soil (3.303 ± 0.035 dS·m^{-1}) and at 55 PTD for the brown soils (2.412 ± 0.016 dS·m^{-1}) and red (1.952 ± 0.016 dS·m^{-1}) (Fig. 5B).

Given the relatively high EC of the irrigation water and the fact that the soils differ in the CEC (which could suggest a salinization of the soil caused by the irrigation and a differential retention of cations,

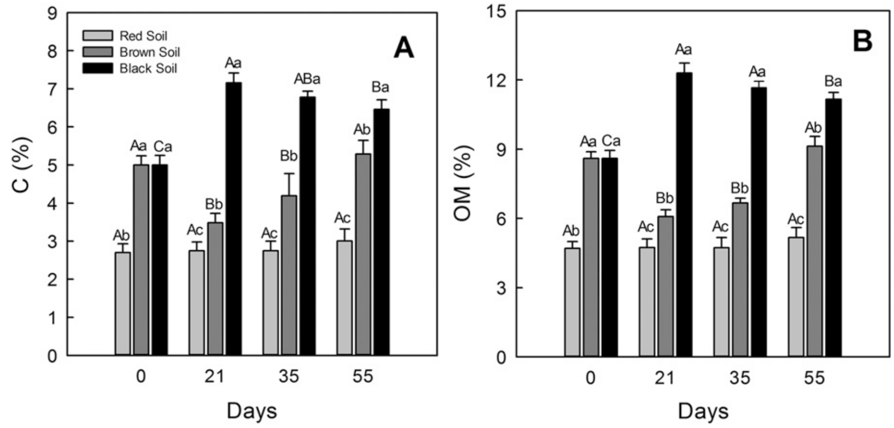

Fig. 6. Dynamics of the C content (**A**) and organic material (OM) (**B**) according to the soil type during the growth of the habanero pepper plants. The data represent the average value of three repetitions, and the vertical lines are the values of standard deviation. Different capital letters indicate significant differences among days in the same type of soil (Tukey's test, $P \leq 0.05$). Different small letters indicate significant differences among soil types on the same day (Tukey's test, $P \leq 0.05$).

such as Na), we decided to evaluate if the content of the same was modified among the soils during the growing cycle. The content of Na was increased at 55 PTD for all the soil types, indicating a differential accumulation per soil type of this cation during the growing cycle. The accumulation of Na was 2.5, 3.9, and 5 times with respect to the initial values for the red, brown, and black soils, respectively (Fig. 5C).

Regarding the percentage of C and OM, it was possible to appreciate that the red soil did not modify these parameters significantly throughout the entire stage evaluated; and these were similar with those presented before the planting of seedlings (Fig. 6). However, in the case of the brown and black soils, significant changes were observed in the initial values and during the different stages evaluated. For the brown soil, the percentages of C and OM diminished by 30% at the 21 PTD with respect to the initial value; but these values were recovered at 55 PTD. On the other hand, for the black soil, both parameters increased by 40% at 21 PTD, with respect to the initial values; and, although they diminished significantly at 55 PTD compared with the values at 21 PTD, they were still 30% higher than the initial data (Fig. 6).

To clarify certain aspects regarding the nutritional quality of the soils during the growth of the plants, the content of the micronutrients Fe^{+2+3}, Mn^{+2}, Zn^{+2}, Cu^{+2}, and B was evaluated in the soils at different moments in the development of the plants.

In the case of Fe^{+2+3}, the black soil always presented the highest values, which fluctuated between six (21 PTD) and eight (35 and 55 PTD) times higher than the values presented by the red and brown soils, both with similar values (Table 1). Regarding the initial values of Fe^{+2+3} in the soils, it was possible to appreciate that the total reduction in the quantity of the same, which occurred at 55 PTD, was not significantly different among the soils, with ≈4 mg·kg^{-1} for the red soil and 3.6 mg·kg^{-1} for the brown and black soils. These values corresponded, in accordance with the initial value, to a reduction of 94% for the red and brown soils and 63% for the black soil. However, the stage at which the greatest reduction of this ion occurred was different according to the soils; in the red and brown soils, the contents diminished mainly in the first 21 PTD, corresponding to a reduction of 80%; between 21 and 35 PTD, the reduction was ≈10% to 12%, and 0.7% (red soil) and 1.3% (brown soil) between 35 and 55 PTD. However, in the black soils, in the first 21 PTD, the reduction was only 16%, with the greatest reduction (40%) between 21 and 35 PTD, and the lowest (6.9%) between 35 and 55 PDT, which is similar to the same stages in the other two soils (Table 1).

With respect to the Mn^{+2}, at 21 PTD, the highest values were detected in the brown soil, while the red and black soils presented similar values. After 35 PTD, the values were always higher in the black soil, followed by the brown, and last, by the red (Table 1). Significantly, the values of this cation were always greater than those found in the soils before transplantation. The highest increase occurred in the black soil at 35 PTD and was more than double in comparison with the initial values of the experiment (Table 1).

At 21 PTD, the highest values of Zn^{+2} were found in the red and black soils; these were significantly lower than those of the brown soil. In contrast, at 35 PTD, a significant reduction in the values of this cation was observed in all the soils, which was more marked in the brown and black; moreover, at 55 PTD, the values of the red soil continued to diminish significantly, while these values increased in the brown and black soils (Table 1). In summary, in the red soil, a reduction was observed in the Zn^{+2} content throughout the whole process. The reduction was 49%, 24%, and 26% at 21 PTD, between 21 and 35 PTD and between 35 and 55 PTD, respectively. The total reduction in this soil was 1.203 mg·kg^{-1}, corresponding to 91%, with respect to the initial values. In the brown soil, the values were reduced at 35 PTD; in this case, the reduction in the first stage (0 to 21 PTD) was 46% and in the second (21 to 35 PTD) 50%, a total reduction of 0.837 mg·kg^{-1} (96% with respect to the initial value). However, in the third stage evaluated (35 to 55 PTD), the content in the soil increased more than 3.5 times, corresponding to a total reduction at 55 PTD of 0.75 mg·kg^{-1} (86% with respect to the initial value). The behavior in the black soil was very similar to that of the brown soil; the reduction in the content of this cation occurred at 35 PTD, with 23% and 71% at 21 and 35 PTD, respectively; while these values increased 3.8 times at 55 PTD, reaching a total reduction, up to this day, of 0.68 mg·kg^{-1} (78% with respect to the initial value) (Table 1).

The contents of Cu^{+2} were always higher in the red soil, in comparison with the brown and black soils; and in every case, the values diminished gradually throughout the whole evaluation period. The greatest reduction occurred at 21 PTD, with 73% (red and brown soils) and 83% (black soil) with respect to the initial values for each soil (Table 1). At 55 PTD, the contents had diminished 1.72, 1.87, and 1.85 mg·kg^{-1}, corresponding to 86%, 94%, and 93% with respect to the initial values for the red, brown, and black soils, respectively.

As with the Fe^{+2+3}, the contents of B were always higher in the black soil, followed by the brown soil, and last, the red soil; this was similar in both soils at 21 PTD (Table 1). Regarding the initial value, at 21 PTD, the values in the brown soil (40%) and in the black soil (15%) had reduced significantly, and those of the red soil had remained similar. However, at 35 PTD, the greatest reduction in the red soil was produced (36%); while in the black soil, the reduction was only 13%, and in the brown soil the values were maintained. At 55 PTD, the contents in the red soil remained similar with those found at 35 PTD; while for the brown and black soils, they had reduced significantly by 10% (Table 1). With a total balance at 55 PTD, the reduction of B was 0.51, 0.55, and 0.62 mg·kg^{-1}, corresponding to 39%, 27%, and 21%, with respect to the initial values, for the red, brown, and black soils, respectively.

Content of the macronutrients N, P, K, Ca, and Mg in soil-root-leaf. Nitrogen, P, and K are the macronutrients required in greater quantity and that limit most severely the productivity of the crops. By analyzing these as a soil-root-leaf continuum, it was possible to observe that at 21 PTD, the content of N was higher in the black soil, followed by the red; the lowest values were found in the brown soil. At 35 PTD, the content of N in each soil was similar with those presented at 21 PTD; in this occasion, the content was similar for the red and black soils and higher than those of the brown soil. However, the behavior presented at 55 PTD was different between the red soil and the brown and black soils; in the red soil, the content of N diminished by 32%, while in

Table 1. Microelement content in the three type of soils, at 21, 35, and 55 d posttransplant (PTD) of habanero pepper plants.

		Fe^{+2+3}			Mn^{+2}			Zn^{+2}			Cu^{+2}			B		
PTD	Soil	mg·kg^{-1}														
21	Red	0.727[z]	(0.080)	Ab[y]	4.480	(0.056)	Cb	0.647	(0.061)	Ab	0.537	(0.006)	Aa	1.297	(0.095)	Ab
	Brown	0.773	(0.100)	Ab	6.407	(0.055)	Ba	0.467	(0.060)	Ab	0.342	(0.010)	Ab	1.203	(0.085)	Bb
	Black	4.793	(0.101)	Aa	4.333	(0.095)	Cb	0.673	(0.060)	Aa	0.333	(0.015)	Ab	2.537	(0.060)	Aa
35	Red	0.297	(0.086)	Bb	6.273	(0.065)	Ac	0.333	(0.051)	Ba	0.365	(0.005)	Ba	0.823	(0.105)	Bc
	Brown	0.293	(0.091)	Bb	6.707	(0.050)	Ab	0.033	(0.025)	Bb	0.213	(0.015)	Bb	1.307	(0.071)	Ab
	Black	2.490	(0.099)	Ba	12.137	(0.070)	Aa	0.052	(0.020)	Cb	0.230	(0.010)	Bb	2.150	(0.090)	Ba
55	Red	0.267	(0.070)	Bb	5.403	(0.057)	Bc	0.117	(0.031)	Cb	0.272	(0.008)	Ca	0.783	(0.090)	Bc
	Brown	0.243	(0.065)	Bb	6.687	(0.090)	Ab	0.120	(0.030)	Bb	0.125	(0.005)	Cc	1.453	(0.070)	Ab
	Black	2.097	(0.119)	Ca	8.717	(0.045)	Ba	0.197	(0.025)	Ba	0.145	(0.005)	Cb	2.382	(0.060)	Aa

[z] The values are the average of three repetitions. The standard deviation data are presented in parentheses.

[y] Different capital letters indicate significant differences among days in the same type of soil (Tukey's test, $P \leq 0.05$), while different small letters indicate significant differences among the type of soil in the same day (Tukey's test, $P \leq 0.05$).

the brown and black soils, these values increased 11 and 4 times, respectively. At this point, the black soil presented values of N that were 6 and 1.2 times higher than the red and brown soils; while in the brown soil, these values were 5 times higher than those of the red soil (Fig. 7A).

The content of N in the roots and leaves of the plants was dependent on the soil type and the plant's physiological stage. At 21 PTD, the content of N in the roots of the plants growing in the red soil was five and seven times lower in comparison with the brown and black soils, respectively; while that of the brown soils was 1.5 times lower than those of the black soils (Fig. 7B). However, in the leaves, no significant differences existed, dependent on the soil type (Fig. 7C).

At 35 PTD, once again, the lowest values were detected in the roots of the plants growing in the red soil, now presenting a lower difference (2.3 and 1.6 times lower in comparison with that of the brown and black soils, respectively). This lower difference was because the values of N in the roots of the plants growing in the red soil increased 2.5 times between 21 and 35 PTD, while those of the brown soil increased only 1.3; and for those of the black soil, the values diminished 1.7 times (Fig. 7B). In the leaves, the N was greater in the plants of the black soil, and the same in the red and brown soils. In the case of the red and brown soils, the levels remained similar with those presented at 21 PTD, while those of the black soil increased significantly during this period (Fig. 7C).

In contrast, at 55 PTD, the highest values of N in the roots corresponded to the plants of the brown soil, followed by the red soil, and last, the black soil. All plants presented an increase in this value, with respect to those presented at 35 PTD; and the increase was 2.5, 1.3, and 1.2 times for the red, brown, and black soils, respectively (Fig. 7B). The plants of the red soil presented the highest values of N in the leaves of this day, with lower and similar values for the brown and black soils; with relation to the 35 PTD, the plants of the red and brown soils increased their values 1.4 and 1.2 times, whereas those of the black soil diminished by 12% (Fig. 7C).

To summarize, from 21 to 55 PTD in the red soil, the content of N diminished by 27%, while this nutrient accumulated 566% and 366% in the brown and black soils. In contrast, the plants of the red and brown soils presented an increase of 640% and 71% in their endogenous contents, while those of the black soil diminished by 20%. Most of the changes, in both reduction and increment, occurred in the roots of the plants.

The content of P in the red and black soils was similar with those of 21 PTD, and it was significantly higher in comparison with the brown soil. In a comparison with the values of the 21 PTD, at 35 PTD, it was possible to observe a reduction of the values in the red soil and a significant increase in the brown soil; while in the black soil, these remained similar—thus, the highest values were detected in the black and brown soils. However, those of the red soil were not significantly different from those of the brown soil. At 55 PTD, the red soil presented the lowest values of P (Fig. 7D).

With regard to the content of this macronutrient in plant tissues, the highest values were obtained in both the root and the leaves of the plants cultivated in red soils, throughout all the evaluations, with the exception of 21 and 55 PTD, where the levels in the root were higher in the plants of the brown soils (Fig. 7E and F).

In relation to the dynamics observed per soil type, the content of P in the roots of the plants cultivated in the red soils increased significantly at 35 PTD, while at 55 PTD, the lowest values were observed; in the leaves, however, the highest values were obtained at 21 PTD, with a subsequent reduction that remained at 55 PTD. However, in the plants growing in the brown soil, the content diminished at 35 PTD and recovered at 55 PDT, with values similar with those presented at 21 PTD, the moment at which this also increased significantly in the leaves (Fig. 7E and F).

The content of K^+ in the red soil remained constant at significantly low values in comparison with the other soils, with no significant variance in these values between the brown and black soils, except at 35 PTD, where the brown soil presented significantly higher values in comparison with the black soil (Fig. 7G).

In the roots, no significant differences were found among the plants growing in different soils at 21 PTD; and at this point, in the leaves, the highest values were found in the plants of the brown soil, followed by the black soil, and, last, the red soil. At 35 PTD, the highest values were found in the roots of plants growing in the brown soil, followed by those of the black soil, and the lowest in the red soil. In the leaves, the highest values were found in the plants growing in the black soil. In contrast with this result, at 55 PTD, the highest values were found in the roots and leaves of the plants in the red soils.

Regarding the dynamics of K^+ in the tissues, a reduction in the content was observed in the roots of all the plants at 35 PTD; while those of the red soil were able to increase this content at 55 PTD, without reaching the values presented at 21 PTD. In the plants of the brown soil, these values continued to diminish up to 55 PTD; and in those of the black soil, no modification was observed (Fig. 7H).

In the leaves, a significant increase was observed only in the plants of the red soil at 55 PTD; while in those of the brown soil, the values were reduced temporarily at 35 PTD and recovered at 55 PTD, up to the initial values. The values for the black soil increased temporarily at 35 PTD and subsequently reduced, presenting similar values between 21 and 55 PTD (Fig. 7I).

The macronutrients Ca^{+2} and Mg^{+2} presented a similar behavior in the soils, where higher contents of these cations were always observed in the brown and black soils, in comparison with the red (Fig. 8A and D). In the roots, small differences were observed in the Ca^{+2} content among the plants of the different soil types—which in some cases were significant. At 21 PTD, the values were similar with each other; while at 35 PTD, they were greater in the roots of the plants growing in the brown soil, and at 55 PTD, significant differences were observed between the brown and black soils, the latter being lower in this case (Fig. 8B). With respect to the dynamics during the time course, the roots of the plants growing in red and black soils always maintained their same values; while for the brown soil, a significant increase was observed at 35 PTD, which was maintained until the end of these evaluations (Fig. 8B).

In the leaves, the highest values of these macronutrients were observed in the plants of

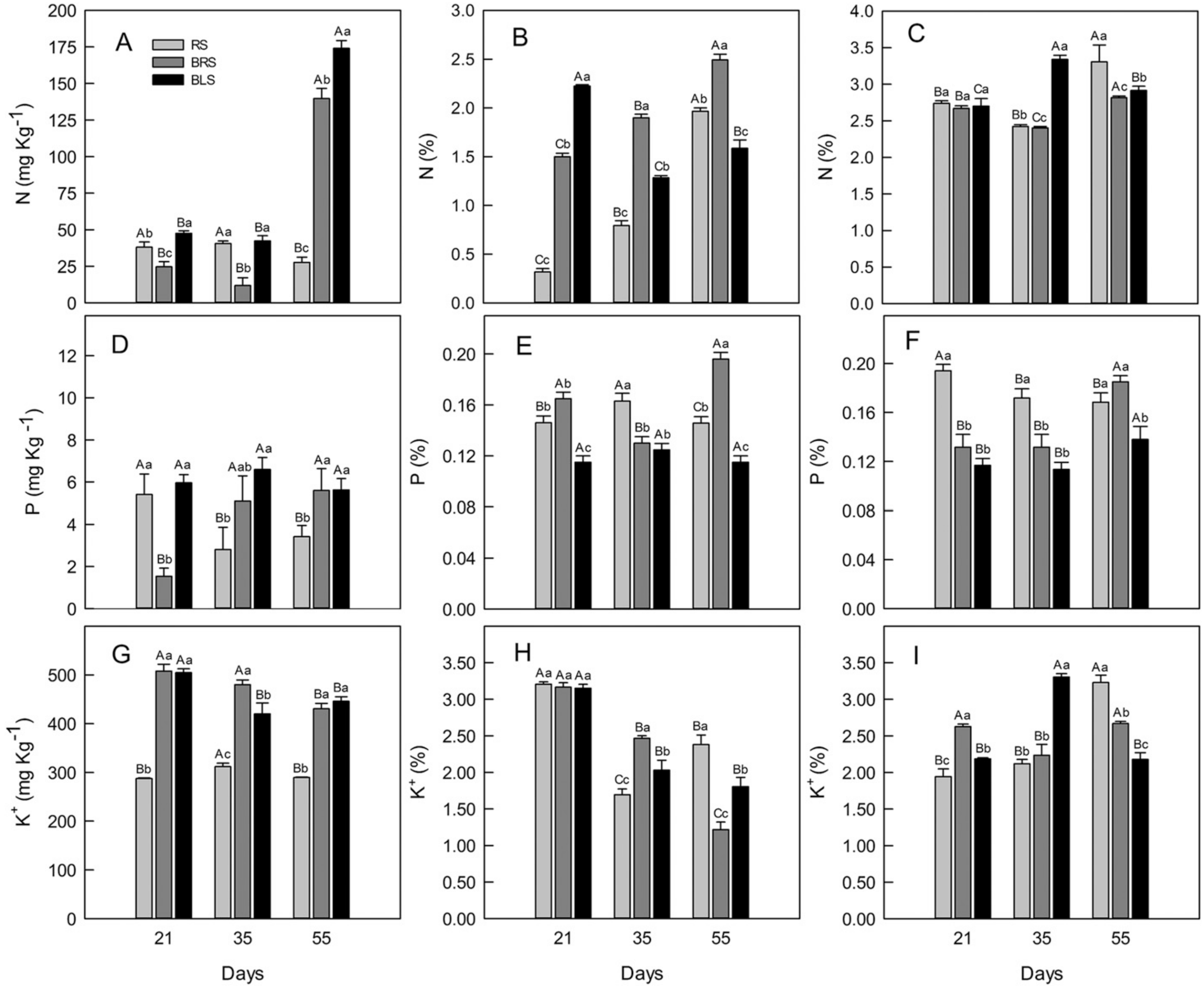

Fig. 7. Content of N (**A–C**), P (**D–F**), and K (**G–I**) in the soils (**A**, **D**, **G**), roots (**B**, **E**, **H**), and leaves (**C**, **F**, **I**) during three moments in the development of habanero pepper. The data are the average of three repetitions. Different capital letters indicate significant differences among days in the same type of soil (Tukey's test, $P \leq 0.05$). Different small letters indicate significant differences among soil types on the same day (Tukey's test, $P \leq 0.05$).

the black soil, in comparison with those of the red soil; while for the brown soil, the values were intermediate, similar with those of the red soil and similar with those of the black soil at 21, 35, and 55 PTD, respectively (Fig. 8C). During the different phenological stages it was possible to observe that the plants of the red soil diminished only in these values at 55 PTD; whereas for the brown and black soils, a continuous decrease was observed, reaching the lowest values at 55 PTD (Fig. 8C).

With respect to the Mg^{+2}, the values in the roots at 21 PTD were 28% and 43% lower in the red and brown soils, respectively, in comparison with the black soils. At 35 PTD, the plants of the black soil reduced their values, and as a result, for this day, their values were similar with those of the plants in the red soil, which had maintained the same values reached at 21 PTD. In the case of the plants of the brown soil, their values were significantly lower than those of the black soil, despite having increased by 27% with respect to their values at 21 PTD (Fig. 8E). At 55 PTD, the lowest values in the roots corresponded with those of the plants in the red soil, which had diminished almost 30% in comparison with those presented at 35 PTD, followed by those of the plants in brown soil (which increased their values of the previous time in 29%). The highest values in this day corresponded to those of the plants of the black soil, which increased only by 10%, with respect to the values of the 35 PTD (Fig. 8E).

Contrasting behaviors were observed in the leaves according to the type of soil and phenological stage. Considering the most contrasting soils, the red and black, it was possible to observe that the values of the plants growing in the red soil were lower at 21 PTD, and this behavior was inverted in the stages of flowering and fructification. The plants of the red soil always maintained similar values of Mg^{+2} in the leaves; while in the plants of the black soil, these diminished after the 35 PTD, remaining in these low values at 55 PTD. The plants of the brown soil presented similar values with those of the red soils in some cases (21 and 55 PTD); and in others, similar with the black soil (35 PTD), fluctuating according to the phenological stage of the plants (Fig. 8F).

Discussion

Plant growth analysis and fruit development and production. In this work, we reported the effect of three types of contrasting soils of the region on the growth and production of habanero pepper. We found that this crop developed more effectively, producing larger fruits, in the red and brown soils, in comparison with the black soil; and influencing, with this behavior, the capacity of differential retention of nutrients among the soils, including the accumulation of Na in the same. It was significant to observe that the plants growing in the brown soil presented

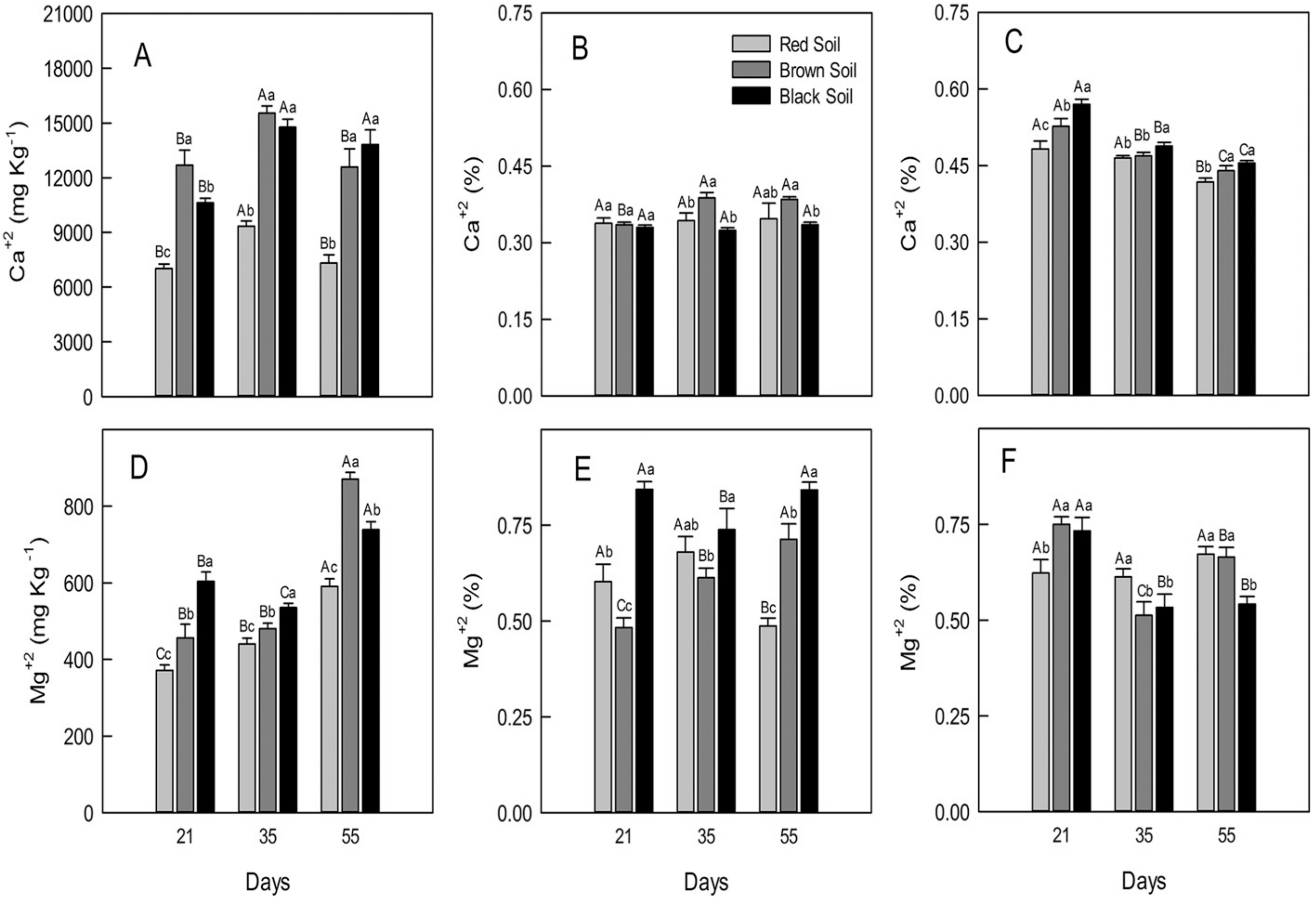

Fig. 8. Calcium content (**A–C**) and magnesium (**D–F**) in the soils (**A**, **D**), roots (**B**, **E**), and leaves (**C**, **F**) during three moments in the development of habanero pepper. The data are the average of three repetitions. Different capital letters indicate significant differences among days in the same soil type (Tukey's test, $P \leq 0.05$). Different small letters indicate significant differences among the soil types on the same day (Tukey's test, $P \leq 0.05$).

variable physiological behaviors, in some cases similarly with the plants of the red soil, and in others similarly with those of the black soil; this finding may be a reflection of their character, which integrates them between the red and black. Bautista-Zúñiga et al. (2003) reported that the red soils presented lower spatial variability, followed by the black, while the brown soils presented the highest variation.

Physico-chemical characterization of the soil and tissue plant. One fundamental problem in the Yucatán is the continuous irrigation of the crops with salt water, which can lead to the salinization of the soils, degradation of the soil, and to a reduction in agricultural yields (Delgado et al., 2010; Pang et al., 2010). The data of EC indicates that, in the black soil, problems of salinity may have been present since 35 PTD; this was not the case for the other red soils (Fig. 5B). Villa-Castorena et al. (2006) indicated that the absorption of nutrients in *Capsicum* reduces if the values of EC of the soils are 3.5 dS·m^{-1}.

Despite the economic importance of the chilis, very little is known regarding the mechanisms of tolerance to the salinity in them. The high concentrations of salts in the soil, mainly NaCl, are responsible for the reduction in the productivity of economically important crops. Chili plants (*C. annuum*), together with the tomato (*S. lycopersicum*) and the potato (*S. tuberosum*), are among the most important crops that are moderately sensitive to salinity (Maas and Hoffman, 1977). Other authors have also considered the chili plants to be sensitive or very susceptible to this abiotic factor (Aktas et al., 2006; Niu et al., 2010a, 2010b). The degree of toxicity depends on the chili species, the cultivar, and the growth conditions (Bojórquez-Quintal et al., 2012, 2014).

At production level, salinity can affect fruit size and weight and can provoke a smaller number of fruits per plant (Chartzoulakis and Klapaki, 2000; Niu et al., 2010b). This effect was particularly obvious in the size and weight of the fruits from the plants growing in the black soil, where a greater quantity of Na was accumulated, in comparison with those of the red soil, where there was a smaller quantity of this element and the fruits were able to achieve a better development (Fig. 4). At a physiological level, the permeability of the membrane, activity of water channels (aquaporins), stomal conductance, photosynthetic rate, and the ion homeostasis are affected (Aktas et al., 2006; Carvajal et al., 1999; Navarro et al., 2003). A combination of various mechanisms of tolerance is suggested to avoid saline stress in chili; the extrusion of Na is not an efficient tolerance strategy (Bojórquez-Quintal et al., 2016)

As can be appreciated in Fig. 6B, the content of OM was very high in the black soils (≥12%), in comparison with the red soil, which presented high values (≈5%). Oorts et al. (2003) reported that the OM can contribute up to 75% to 80% in the CEC; in our case, these parameters appear to coincide in the 21 and 55 PTD, but not for 35 PTD (Figs. 5A and 6B), indicating that another parameter, different to the content of OM, is having an influence on the CEC of the soils. Martínez et al. (2008) suggested that the OM can favor the retention of humidity, although they also mention that this favors the proportion of large pores in the soil that retain water with less energy.

The factor of differential retention/absorption of macronutrients among the different types of soil and plants could be one of the more important factors to explain the results obtained in the development of the fruits in this work. Although the content of N was also seen to be very high for the black soils, particularly at 55 PTD, it is important to note that the N evaluated corresponds to the total N of the soil (organic plus inorganic forms) and should not be taken as available N for the plants. For example, it has been reported that, as the salinity of the soils increases, N diminishes in the form of nitrate, a very important source of N for the growth and development of the crops (Min et al., 2016). Moreover, under these conditions, the concentrations of N in the form of ammonia can increase because the nitrification is reduced by high concentrations of salt (Bernhard and Bollmann, 2010). The ammonium in high quantities can be toxic for the crops.

The joint effect of high concentrations of N and the salinity has been reported as a factor that reduces the yield in *Capsicum*, especially when the plants are cultivated at high temperatures (Villa-Castorena et al., 2003). Our results indicate that the plants growing in the red soil may have had a greater absorption of this nutrient and a more efficient transport of the same to the leaves, in comparison with the black soil.

The soil P levels found in this work remained below those reported by Borges-Gómez et al. (2014) for 67% of the soils analyzed by these authors, but coincided with 21% of the remaining soils; all of which were in the area where the habanero pepper is cultivated, in the Peninsula of Yucatán. These levels are averages; note that, given the neutral pH of the soils, this element should present low solubility (Johnson et al., 2003). Borges-Gómez et al. (2008) considered that the critical level of P in the soils for the cultivation of habanero pepper is 11.9 $mg \cdot kg^{-1}$; and as can be observed in Fig. 7D, in every case the levels detected were below this value.

The variation in the content of K among soils can be attributed to the nature and the proportion of the colloids in the soils (Borges-Gómez et al., 2005). This element is placed in fifth place, according to the requirements of the plants, after C, O, H, and N (Marschner, 1995). It is important to note that in this work the exchangeable K was determined, which is not the chemical form directly available for the plants. The values reported in our work for K in the soils coincide with those previously reported by other authors (Bautista-Zúñiga et al., 2003), and all the soils can be classified as soils rich in K.

However, it is well known that the soils rich in exchangeable K are not always rich in soluble K, which is the chemical form available for the plants. Factors that have an influence on this relationship include the type and quantity of clay, another being the content of OM (Borges-Gómez et al., 2005). Borges-Gómez et al. (2005) observed differences of up to six times in the effective coefficient of K among the soils of Yucatán, this parameter being, in conjunction with the buffering power of the soil, what determines the availability of this cation for the crops.

As can be observed in Fig. 8, all the soils presented very high levels of Ca and mediums of Mg, which concurs with the reports by Borges-Gómez et al. (2014) for the soils in which the habanero pepper is cultivated in Yucatán, which are a result of their calcareous origin (Wilson, 1980). This macronutrient diminished in the leaves of the plants growing in the red soil, only between 35 and 55 PTD, in contrast with those of the black soil, in which the diminishment was observed in all the stages evaluated. These findings could be indicating that, in those of the red soil, this element may have been translocated to the fruits for use in their development. As for the micronutrients in the soil, the contents of Fe were very low in the red and brown soils throughout the evaluations and were even lower in comparison with the 24 soils studied by Borges-Gómez et al. (2014). In the black soil these values were low and coincided with 63% of the soils evaluated by these authors. In contrast, the contents of Mn and Cu were high; although it is important to take into consideration that according to the pH, these micronutrients are not sufficiently available with low solubility due to the type of calcareous soil (Arizmendi-Galicia et al., 2011).

If the fertility of the soil is defined as the status of the soil–plant system (Comerford, 1998), it can be observed that, even though the black soil presented the highest contents of the macronutrients N, P, and K, in comparison with those present in the red soil at 55 PTD, the plants did not increase their endogenous values, but rather the opposite. The plants of the red soil presented values higher than these nutrients in both the root and the leaves (Fig. 7). Regarding the mechanisms that describe the soil-plant status, we consider that the differences in the processes of nutrient liberation from the solid phase to the liquid phase of the soil (buffering capacity of the soil) and the movement of the nutrients through the soil solution to the roots of the plant among the soil types, are the elements that are having a greater impact on the results observed. However, changes in root absorption cannot be ignored, even though no significant differences were found in root growth among the plants of the red and black soils on this day (Fig. 1).

The difference observed in the development of the fruits of the habanero chili among the soil types could not be attributed only to their nutritional quality; another important aspect that must be considered is the differential presence of microorganisms according to the soil type. The soils were not sterilized in this work, so as to simulate as close as possible the natural conditions in which habanero chili grows in these types of soils in Yucatán.

It has been reported that red soils present a bacterial diversity, at a species level, twice as large as that of the black soils, with the red soil strongly dominated by *Acidobacteria* (83%); while for the black soil, the most abundant phylum was that of *Actinobacteria* (43.7%), followed by *Acidobacteria* (26.9%) and *Proteobacteria* (23.6%) (Estrada-Medina et al., 2016). According to their phylogenetic diversity, ubiquity, and abundance, it has been suggested that *Acidobacteria* has an important ecological role and a significant metabolic versatility (Ward et al., 2009). The fungal community was found to be even more contrasting and appears to be unique for each type of red or black soil (Estrada-Medina et al., 2016). These microorganisms, associated with each type of soil, can contribute to the availability of nutrients for the plants and subsequently to the production of the habanero pepper.

The problems of salinity are also closely linked to the soil microbiota (Min et al., 2016; Shen et al., 2008) and to the N fertilization (Lee and Caporn, 1998; Min et al., 2016; Sarathchandra et al., 2001). Shen et al. (2008) reported that the salinization causes a significant reduction in the functional diversity of the soil microorganisms, a situation that may be the result of osmotic stress (Li et al., 2014). Moreover, it has been reported that high levels of N fertilization provoke the same effect (Sarathchandra et al., 2001), and low levels induce the opposite effect (Lee and Caporn, 1998). Given the high levels of N (Fig. 7A) and Na (Fig. 5C) obtained on day 55 in the black soils, in comparison with those presented in the red soil, it is suggested that the black soils present a lower microbiological diversity compared with that of the red soils, even lower than those reported by Estrada-Medina et al. (2016) for soils without salinity.

Studies could be carried out on the soil microbiota under these growth conditions to know its contribution to the development of chili, together with the physical and chemical properties of the soils.

Taking our data as a whole, we recommend that special care be taken with the quality of the water used for irrigation and with the fertilization regime. Inferior water can worsen the problems of salinity in the soils where habanero pepper is cultivated, particularly if black soils are involved with a high content of OM. These results are extremely useful in the preparation of agricultural plans, given the enormous problems of saline intrusion on a global scale. For example, in the Yucatán, only one section of 28.7% is recommended for agriculture—the rest is contaminated with salinity (Delgado et al., 2010).

Conclusions

The habanero chili achieved a better development of its fruits growing in red and brown soils, in comparison with the conditions of black soil. Among the factors that could explain this behavior, a greater retention of Na in the black soils is proposed, which could lead to a reduction in the availability and the absorption of other nutrients important to plant growth, as well as the accumulation in large quantities of other toxic nutrients in the black soil (such as ammonium) and changes in the microbiota of the soils under these conditions.

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