Nickel increases productivity, Ca accumulation and reduces blossom-end rot in tomato

Fernando Giovannetti Macedo, Wanderley José De Melo, Denise De Lima Delarica, Renata Beatriz Cruz, Elcio Ferreira Santos, Gabriel Maurício Peruca De Melo, Ben Hur Mattiuz, Mara Cristina Pessôa da Cruz and Arthur Bernardes Cecílio Filho

ABSTRACT
Blossom-end rot (BER) is a physiological disorder related to calcium (Ca) deficiency in tomato fruits. However, adequate Ca supply is not sufficient to inhibit the BER incidence. The Ni-Ca interaction has increased the Ca content in Ni hyperaccumulators plants. However, studies with commercial plants are still incipient. The objective of this work was to evaluate the effect of Ni-Ca interaction in tomato plants, focusing on yield and incidence of BER. We carried out two trials. The first trial two Ca doses was used: sufficient Ca 0.70 g kg⁻¹ (Ca S) and deficient Ca 0.35 g kg⁻¹ (Ca D) and; four Ni doses applied via substrate (0.0; 0.5; 1.0 and; 2.0 mg kg⁻¹). In the second trial, the same Ca doses of the first trial and four doses of Ni (0.0; 0.08; 0.42 and; 0.84 mM) applied, via foliar, at the beginning of flowering were used. We verified that the Ni-Ca interaction increased the tomato fruits yield, the shoot calcium accumulation reduced the BER incidence and increased the time of fruit color change (green to red). Even under stressed conditions such as a low Ca availability. Both Ni application ways showed positive results for fruit yield and decreased BER incidence.

Introduction
Tomatoes are considered a high-risk crop due to the production cost and susceptibility to biotic and abiotic factors. One of the main factors responsible for the tomato yield loss is the blossom-end rot (BER), a name given to the multifactorial physiological disorder related to calcium (Ca) deficiency in fruits, attributed in part to the low Ca mobility in plants (Hawkesford et al. 2012).

Fruits with BER have localized necrosis, become unfit for commercial use. The sequence of events preceding BER development is increasing membrane leakage, cell plasmolysis, and membrane breakdown that lead to the water-soaked symptoms on the blossom-end fruit surface (Ho and White 2005). Because BER is diagnosed during the fruit development period, by that time, much of the money has already been spent on tomato production, causing a significant economic loss. Although BER is attributed to Ca deficiency, the Ca adequate supply has not provided efficient BER control (Wissemeier and Zuhlke 2002). BER is also be triggered by abnormal cellular Ca²⁺ partitioning...
and distribution that leads to a cellularly localized Ca\(^{2+}\) deficiency (De Freitas et al. 2012). In addition, the total fruit tissue Ca\(^{2+}\) content is not the only cause of BER development. Fruits with BER can showed equal or higher Ca\(^{2+}\) concentrations than fruit without symptom (Nonami et al. 1995). The incidence of BER is considered a multifactorial physiological disorder, which may be associated with genetic factors, high fruit growth rate (Fontes 2003) and hormonal imbalance (De Freitas et al. 2012), abiotic factors, such as: salinity, high temperatures (Arruda et al. 2011). However, accumulation of Ca in fruit is determined not only by their relative prevalence and mobility in the phloem and xylem, but also by nutrient interactions (DeKock et al. 1979, 1982). In this sense, the Ni-Ca interaction can attenuate the BER incidence in tomatoes.

The Ni-Ca interaction has been studied for a long time (Crooke and Inkson 1955) and the effect of Ca in mitigating Ni toxicity is already known (Gabrielli and Pandolfini 1984; Sreekanth et al. 2013). Studies have shown that in Ni hyperaccumulators plants, the Ni can be uptake via Ca channels (Mohseni et al. 2019). It is also known that urease, a Ni-dependent enzyme (Fabiano et al. 2015), can influence the transport and Ca influx to the cells (Follmer et al. 2004). However, studies using low doses of Ni aiming at the Ni nutritional aspects, have not been carried out. Regarding reproductive structures, the Ni application has increased the number of flowers (Ghasemi et al. 2014) and reduced the abortion of fruits (Malavolta et al. 2006), in addition to the effect of prolonging the maturation time by reducing the ethylene production of the fruits (Smith and Woodburn 1984).

Thus, our hypothesis is that the Ni-Ca interaction can increase the shoot Ca accumulation of tomato plants, reduce the BER incidence and increase fruit yield. The goal this work was to evaluate the effect of Ni-Ca interaction in tomato plants, focusing on yield and incidence of BER.

**Materials and methods**

**Experiment description**

Two trials were carried out in greenhouses (with maximum and minimum mean temperatures of 37 and 18°C, respectively). Tomato plants were grown in pots with capacities of 10 dm\(^3\), filled with 8 kg of substrate (a 1:1 ratio of vermiculite and sand). The sand had been previously washed with an HCl solution (0.5 mol L\(^{-1}\)), followed by double washing with deionized water (Gondim et al. 2015).

**Experimental design**

For both trials, carried out simultaneously, a random design was used in a 2 × 4 factorial scheme (2 Ca doses and 4 Ni doses) with five replicates.

Trial I: two Ca doses (0.35 and 0.70 g kg\(^{-1}\)), corresponding to 50% (deficient Ca – Ca D) and 100% (sufficient Ca – Ca S) of the Ca dose recommended for tomato plants (Schwarz et al. 2014), and four doses of Ni (0.0 as control, 0.5, 1.0 and 2.0 mg kg\(^{-1}\)) were applied in the substrate (Macedo et al. 2016).

Trial II: the same doses of Ca from the first trial were applied to the substrate and four Ni doses (0.0 as control; 0.08; 0.42 and 0.84 mM) were applied to the leaves at the beginning of flowering (Kutman et al. 2013).

**Plant cultivation**

**Nursery**

In the first 30 days, the tomato plants were grown in a greenhouse with light control (50% sunlight retention – nursery). Trays with 128 individual cells filled with coconut fiber substrate, Debora Victory hybrid tomato seeds and the solution of Hoagland and Arnon (1950) diluted (1: 5; 20% of ionic strength) were used. After this period, the plants were transplanted to pots. On the day of transplantation, tomato plants had 9.85 g kg\(^{-1}\) ± 0.23 Ca and 1.5 mg kg\(^{-1}\) ± 0.51 Ni (dry matter).
**Cultivation of tomatoes in pots**

In pots filled with 8 kg of the mixture of vermiculite and sand, the following nutrients were applied: N 1.5, P 0.2, K 1.5, Mg 0.2, S 0.4, Fe 0.007, Mn 0.006, Zn 0.008, B 0.01, Cu 0.008, and Mo 0.001 g kg⁻¹ (Schwarz et al. 2014), in addition to Ca according to the treatments. For Ni application to the substrate (Trial I), a solution of NiCl₂ · 6 H₂O (13.63 mM L⁻¹) was used, which was applied in a volume in accordance with each treatment (Macedo et al. 2016). One day after the fertilizer applications, two plants per pot were transplanted and cultivated together in order to cause more stress and to stimulate BER incidents. The plants were cultivated with only one main stem. At the beginning of flowering (Trial II), a single application of NiCl₂ · 6H₂O on the leaves was performed. We used the following solutions: 0.0; 0.002; 0.01; and 0.02% (w/v) NiCl₂ · 6H₂O, corresponding to 0.0; 0.08; 0.42 and 0.84-mM Ni (Kutman et al. 2013).

At 30 and 60 days after transplant (DAT), the following agronomic traits were evaluated: plant height (PH), stem diameter (SD) at 5 cm from the base, bud numbers, and photosystem efficiency (PhE). The PhE was estimated by measuring chlorophyll fluorescence using a (Opti-sciences – Os30P, USA) chlorophyll fluorimeter. Plants were allowed to adapt in the dark for a minimum of 20 min before excitation with a 1 s pulse of red light. The following parameters were measured using a Handy-PEA Continuous Excitation Chlorophyll Fluorimeter (Hansatech Instruments Ltd, United Kingdom): minimum chlorophyll fluorescence after excitation (F₀), and maximum chlorophyll fluorescence after excitation (Fₘ). These two parameters were used to calculate the variation in fluorescence calculated from F₀ and Fₘ (Fᵥ), and the ratio of variable fluorescence and maximum fluorescence (Fᵥ/Fₘ) (Tiwari et al. 2017).

When the plants presented the first ripe fruit (Raij et al. 1997), the diagnose leaf was collected to monitor nutrients (supplementary Table 1). At 110 DAT, the BER incidence were evaluated. The ratio between the total number of fruits and the number of fruits with BER incidence was calculated. The results were presented in percentage of fruits with BER. After these evaluations, a plant from each pot was harvested to evaluate the accumulation of Ca and Ni in the shoot dry mass (with the exception of fruits). The concentration of Ca and Ni of the shoot and macro and micronutrients of the diagnostic leaves was determined after digestion with nitric and perchloric acids (Miller 1998), and analyzing the extract via ICP-OES spectrometry. Ca and Ni accumulation in shoots were calculated by multiplying the shoot dry mass by the element’s concentration in the shoot.

At 130 DAT, the second plant was harvested to evaluate the productivity of fruits. Only the healthy fruits without BER symptoms were considered for productivity. One fruit of each plant was collected to monitor the color change time (from green to red). The middle third of each fruit was circled as a target, and colorimeter (I – a – b) readings were performed for 15 days at the same target. The variation of the ‘a’ coordinate’s green/red as a function of time (days) was monitored.

**Statistical analysis**

The results were analyzed using the software SAS System for Windows 6.11 (SAS Institute 1996). The analysis of variance (ANOVA) was carried out, and when the F test was significant (p < 0.05), the Tukey's HSD test was used to identify significant differences among the treatments.

**Results**

**General results**

The Ni – Ca interaction showed positive results for yield healthy fruit, dry weight, photosynthetic efficiency, Ca accumulation in the shoot, BER incidence and time for fruit color change from green to red. At least one of the tested Ni – Ca combinations showed superior results compared to the control treatment for the evaluated variables. However, the Ni application induced growth reduction for the plants that received the highest dose of Ni applied to the substrate, in the both Ca doses evaluated.
Agronomic traits

At 30 DAT, the plants grown under Ca S, showed growth reduction at the Ni highest applied dose for both ways (foliar and substrate via) (Supplementary Table 2). The other agronomic traits evaluated at 30 DAT were not affected by the treatments (SD 6.22 ± 0.77 for Ni substrate and 6.15 ± 0.83 Ni foliar; bud numbers 12.63 ± 0.99 for Ni substrate and 12.33 ± 1.61 for Ni foliar). At 60 DAT, the treatments did not influence tomato plants: at PH (Ni substrate 185 ± 16, Ni foliar 182 ± 15 cm), bud numbers (Ni substrate 12.63 ± 0.99, Ni foliar 12.33 ± 1.16), SD (Ni substrate 6.2 ± 0.77 mm; Ni foliar 6.16 ± 0.83 mm), and phenological stage (6.2) were not affected by the treatments.

Yield

The shoot dry mass production was increased in both evaluated Ca doses (Ca S and Ca D) by the application of 0.5 and 1.0 mg kg⁻¹ of Ni via substrate (Figure 1(a,b)). Ni application via substrate increased the productivity of tomato fruits in the two doses of Ca (Ca S and Ca D) evaluated. In plants grown with Ca S, the application of 0.5 mg kg⁻¹ of Ni in the substrate increased the fruit yield by 22% compared to the control treatments. In plants grown with Ca D, the application of 1.0 mg kg⁻¹ of Ni increased fruit yield by 33% compared to the control treatment.

For tomato plants grown with Ca S, the Ni application via foliar showed the fruit yield difference only between the two highest Ni doses applied (0.42 and 0.84 mM), where the highest Ni dose

![Figure 1](image-url)
applied showed the highest yield. In both doses of Ca applied, the shoot dry mass yield was greater in the control treatment and in the dose of 0.08 mM of Ni applied via leaf. Plants grown under CaD increased fruit yield by 22% compared to plants in the control treatment, when they received the highest dose of Ni (0.84 mM Ni) applied via foliar (Figure 1(c,d)).

**Photosystem efficiency – PhE**

At 30 DAT, plants grown under Ca S showed higher PhE when they received 0.5 and 1.0 mg dm$^{-3}$ of Ni via substrate than plants of the control treatment and the highest dose of Ni applied (2.0 mg dm$^{-3}$) (Figure 2a). At 60 DAT, the plants of all treatments that received Ni showed a higher PhE than the plants of the control treatment. At 30 DAT, plants grown under Ca D, showed PhE variation only between doses 0.5 and 2.0 dm$^{-3}$ of Ni applied via substrate. The other doses of Ni and control treatment did not differ (Figure 2b). At 60 DAT, for the plants grown under Ca D, there was no influence of Ni for PhE (Figure 2(a,b)). At 30 DAT, for plants grown under Ca S, the Ni application via foliar showed a higher PhE than the control treatment in all Ni doses evaluated. At 30 DAT, the highest PhE was observed in plants grown under Ca D and 0.08 mM Ni via leaf. At 60 DAT, there was no influence of treatments for PhE (Figure 2(c,d)).

![Figure 2](image-url)

**Figure 2.** Photosystem Efficiency (Fv/Fm) as a function of Ni – Ca interaction. (a-c) data collected at 30 days after treatments. (b-d) 60 days after treatments. (a-b) Ni applied in the substrate. (c-d) Ni applied via foliar. Different lowercase letters are significantly comparing Ca supply and different uppercase letters are significantly different comparing Ni dosages, by Tukey’s test (p < 0.05).
Figure 3. Ni and Ca concentration in the shoot of tomato plants as a function of the Ni – Ca interaction. (a-b) Ni applied in the substrate. (c-d) Ni applied via foliar. Different lowercase letters are significantly comparing Ca supply and different uppercase letters are significantly different comparing Ni dosages, by Tukey's test (p < 0.05).

**Accumulation of Ca, Ni, BER incidence**

For all treatments, an increase in Ni concentration was observed depending on the application of the element (Figure 3[a,d]). The increase in Ca concentration as a function of Ni doses in plants grown under Ca S showed no significant difference compared to the control treatment (Figure 3a). For plants grown under Ca D, the application of 0.5 mg kg⁻¹ of Ni increased the accumulation of Ca in the shoot by 60% compared to the plants of the control treatment (Figure 3b). The application of 0.08 mM Ni increased the accumulation of Ca by 40% and 30% compared to the control treatment plants grown under Ca S and Ca D (Figure 3[c,d]), respectively. Plants grown under Ca S, the application of 0.5 mg kg⁻¹ of Ni reduced the incidence of BER by 60% compared to the control treatment (Figure 4). Plants grown under Ca D, the application of 0.5 mg kg⁻¹ of Ni reduced the incidence of BER by 30% compared to the control treatment. The application of Ni via leaf did not reduce the BER incidence.

**Fruit color change**

For plants grown under Ca S, the color change of fruits from green to red (Figure 5) was 6 days slower in fruits of plants that received 0.5 mg kg⁻¹ of Ni via substrate than the plants fruits from the control treatment and the greater Ni dose applied (2.0 mg kg⁻¹). For plants grown under Ca D the color change of fruits from green to red was 5 days slower in fruits from plants that received 1.0 and 2.0 mg kg⁻¹ of Ni via substrate than fruits from the control treatment plants. For plants grown under Ca S,
Figure 4. Percentage of tomato fruits with BER incidence as a function of Ni – Ca interaction. (a) Ni applied in the substrate. (c) Ni applied via foliar. Different lowercase letters are significantly comparing Ca supply and different uppercase letters are significantly different comparing Ni dosages, by Tukey’s test (p < 0.05).

the color change of fruits from green to red was 5 days slower in fruits from plants that received any dose of Ni via leaf than the fruits from plants of the control treatment. The smallest time variation for fruit color change was observed in plants grown under Ca D and which received Ni via leaf. In these conditions, the application of any dose of Ni delayed the color change of the fruits (from green to red) in 2 days compared to the fruits of the control treatment.

Discussion

Tomato is the most economically important vegetable species in the world (Schwarz et al. 2014) and represents 14% of all vegetables produced. Annually, BER has caused great damage to tomato farmers, mainly because it occurs in the fruiting phase of the plants, when agricultural inputs have already been applied. Although BER is caused by Ca deficiency in the distal part of fruits, it is known that Ca is not the only factor responsible for the occurrence of BER (De Freitas et al. 2014). These results show that the cultivation of plants under Ca level adequate is not enough to inhibit the incidence of BER (Petersen, Willumsen 1992; Nonami et al., 1995). Therefore, Ca should not be studied in isolation (Suzuki et al. 2003; De Freitas et al. 2012).

The Ni-Ca interaction increased the tomato fruits yield, the shoot Ca accumulation and reduced the BER incidence. The yield increases of agricultural crops from Ni application (low doses) have been reported since the middle of the last century (Roach and Barclay 1946). Additionally, the existence of hidden deficiencies of Ni in agricultural crops was recently questioned due to intensive land use (successive crops), without the restitution of Ni to the soil (Freitas et al. 2018). For both Ni supply way (via leaf or via substrate) the Ni-Ca interaction showed positive results. The increases of plant yield due to the Ni application has been attributed to the activity of Ni-dependent enzymes related to the N metabolism (Harish Sundaramoorthy et al. 2008), and photosynthetic activity (Macedo et al. 2016; Shahzad et al. 2018). In this work, we verified the PhE increase as a function of Ni application in plants grown under Ca S.

We highlight the results verified in the Ca D treatments (50% of the Ca dose recommended) and the doses of 0.5 and 1.0 mg kg⁻¹ of Ni that presented accumulation of Ca in the shoot similar to that of the plants that received 100% of the recommended Ca dose (Ca S). Several studies have suggested a linkage between the urease, a Ni-dependent enzyme, and the Ca channels in microorganisms (Alves et al. 1992) and plants (Follmer et al. 2004), even the Ca influx in the cells. Recently our study group showed that the application of Ni increased the urease activity in tomato fruits (cv Micro-Tom) and inhibited the incidence of BER, even in plants
grown with limited Ca availability (Macedo et al. 2021). It was verified in Ni hyperaccumulators plants, the Ca and Ni uptake can occur via Ca channels (Mohseni et al. 2019). In addition, in Ni hyperaccumulators plants, the increase in Ca accumulations as a function of Ni have been reported (Küpper et al. 2001). The increases of Ca content in the plant tissues due the low Ni doses application has been reported for several crops (Crooke and Inkson 1955; Palacios et al. 1998; Barsukova and Gamzikova 1999; Paiva et al. 2003; Ahmad et al.011). However, these results have not been the subject of discussion, considering that the studies aimed to evaluate the toxic effect of Ni in plants. Thus, the behaviors of cultivated plants with the low doses of Ni applied were not discussed from the nutritional point of view in these studies.

The localized Ca deficiency in fruits has been largely associated with abiotic stress conditions, especially high temperatures, common in regions where tomatoes are grown (Suzuki et al. 2003). We found, in this work, that the Ni-Ca interaction reduced the incidence of BER. Ni-dependent enzymes such as urease and glyoxalase I, has been reported to alleviate stress conditions (Kaur et al. 2014; Mustafiz et al. 2014; Fabiano et al. 2015; Barcelos et al. 2018). Although the Ni role in reproductive structures is still unknown, the Ni application has increased the number of flowers in the Ni

*Figure 5.* Shelf life of tomato fruits as a function of Ca and Ni dosages. Transition time (days) of tomato fruits from green to red color. Measurements of coordinate A made by colorimeter L-A-B. Negative numbers (-): referring to the green color. Positive numbers (+): referring to red color. 0: transition from green to red.
hyperaccumulator plants (Ghasemi et al. 2014) and decreased fruits abortion in orange trees (Malavolta et al. 2006).

The Ni-Ca interaction increased the time for the fruit to change color from green to red. Highlighting the treatments that contain Ni via foliar. Fruit color change has been associated with fruit ripening, governed by ethylene. The effect of Ni on reducing ethylene production is well known (Smith and Woodburn 1984; Kutman et al. 2013). The increase in fruit ripening time is also important because increases the shelf life of fruits.

Finally, our results reinforce the narrow interval between adequate and toxic Ni doses for plants (Kutman et al. 2013; Williams 2015; Shahzad et al. 2018). Several agronomic traits evaluated in these studies (fruit yield, PhE at 30 DAT, BER incidence and fruit color change time), had a negative effect on plants grown with 2.0 mg kg\(^{-1}\) of Ni, suggesting toxic levels of Ni.

**Conclusion**

We verified that the Ni-Ca interaction increased the tomato fruits yield, the shoot Ca accumulation. Even under stressed conditions such as a low availability of Ca. The Ni application via substrate reduced the BER incidence and the Ni application via foliar increased the time of fruit color change (green to red). For the Ni application via substrate the narrow interval for the adequate and toxic doses of Ni for the plants was observed. The highest Ni doses (2.0 mg kg\(^{-1}\) Ni) decreased tomato yield.

**Disclosure statement**

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**ORCID**

Fernando Giovannetti Macedo [http://orcid.org/0000-0002-6683-9162](http://orcid.org/0000-0002-6683-9162)
Wanderley José De Melo [http://orcid.org/0000-0003-2683-0347](http://orcid.org/0000-0003-2683-0347)
Denise De Lima Delarica [http://orcid.org/0000-0002-8529-6976](http://orcid.org/0000-0002-8529-6976)
Renata Beatriz Cruz [http://orcid.org/0000-0003-0703-8901](http://orcid.org/0000-0003-0703-8901)
Elcio Ferreira Santos [http://orcid.org/0000-0002-1148-0527](http://orcid.org/0000-0002-1148-0527)
Gabriel Maurício Peruca De Melo [http://orcid.org/0000-0002-1634-4145](http://orcid.org/0000-0002-1634-4145)
Ben Hur Mattiuz [http://orcid.org/0000-0001-6711-3374](http://orcid.org/0000-0001-6711-3374)
Mara Cristina Pessôa da Cruz [http://orcid.org/0000-0002-6000-878X](http://orcid.org/0000-0002-6000-878X)
Arthur Bernandes Cecílio Filho [http://orcid.org/0000-0002-6706-5496](http://orcid.org/0000-0002-6706-5496)

**References**

Alves EW, Ferreira AT, Ferreira CT (1992) Effects of canotoxin on the Ca(2+)-ATPase of sarcoplasmatic reticulum membranes. Toxicon. 30: 1411–1418
Arruda SJ Jr, Bezerra Neto E, Barreto LP, Resende LV. 2011. Blossom-end rot and productivity of tomatoes as a function of calcium and ammonium contents. R Caatinga. 24:20–26.
Barcelos JPQ, Reis HPG, Godoy CV, Gratão PL, Furlani Junior E, Putti FF, Reis AR (2018) Impact of foliar nickel application on urease activity, antioxidant metabolism and control of powdery mildew (Microsphaera diffusa) in soybean plants. Plant Pathol. 67: 1502– 1513.
Barsukova VS, Gamzikova OC. 1999. Effects of nickel surplus on the element content in wheat varieties contrasting in Ni resistance. Agrokhimyiya. 1:80–85.
Croke WM, Inkson RHE. 1955. The relationship between nickel toxicity and major nutrient supply. Plant Soil. 6(1):1–15. doi:10.1007/BF01393752.

De Freitas ST, Jiang CQ, Mitcham EJ. 2012. Mechanisms involved in calcium deficiency development in tomato fruit in response to gibberellins. J Plant Growth Regul. 31(2):221–234. doi:10.1007/s00344-011-9233-9.

De Freitas ST, McElrone AJ, Shackel KA, Mitcham EJ. 2014. Calcium partitioning and allocation and blossom-end rot development in tomato plants in response to whole-plant and fruit-specific asbscisic acid treatments. J Exp Bot. 65(1):235–247. doi:10.1093/jxb/ert364.

DeKock PC, Hall A, Boggie R, Inkson RHE. 1982. The effect of water stress and form of nitrogen on the incidence of blossom-end rot in tomatoes. J Sci Food Agric. 33(6):509–515. doi:10.1002/jsfa.2740330603.

DeKock PC, Hall A, Inkson RHE, Robertson RA. 1979. Blossom-end rot in tomatoes. J Sci Food Agric. 30(5):508–514. doi:10.1002/jsfa.2740300511.

Fabbiano CC, Tezotto T, Favarin JL, Polacco JC, Mazzafera P. 2015. Essentiality of nickel in plants: a role in plant stresses. Front Plant Sci. 6:754. doi:10.3389/fpls.2015.00754.

Follmer C, Wassermann GE, Carlini CR. 2004. Separation of jack bean (Canavalia ensiformis) urease isofoms by immobilized metal affinity chromatography and characterization of insecticidal properties unrelated to ureolytic activity. Plant Sci. 167(2):241–246. doi:10.1016/j.plantsci.2004.03.019.

Fontes PCR. 2003. Podridão apical do tomate, queima dos bordos das folhas em alface e depressão amarga dos frutos em maçã: deficiência de Ca7? Hortic Bras. 6(2):145. doi:10.1590/S0102-05362003000200003.

Freitas DS, Rodak BW, Reis AR, Reis FB, Carvalho TS, Schulze J, Carneiro MAC, Guilherme LRG. 2018. Hidden Nickel deficiency? Nickel fertilization via soil improves nitrogen metabolism and grain yield in soybean genotypes. Front Plant Sci. 9:614. doi:10.3389/fpls.2018.00614.

Gabbrielli R, Pandolfini T. 1984. Effect of Mg2+ and Ca2+ on the response to nickel toxicity in a serpentine endemic and nickel-accumulating species. Physiol Plant. 30(4):540–544. doi:10.1111/j.1399-3054.1984.tb02796.x.

Ghasemi R, Chavoshi ZZ, Boyd RS, Rajakaruna N. 2014. A preliminary study of the role of nickel in enhancing flowering of the nickel hyperaccumulating plant Alyssum inflatum Nyár. (Brassicaceae). South African J Bot. 92:47–52. doi:10.1016/j.sajb.2014.01.015.

Gondim ARO, Prado RM, Cecilio Filho AB, Alves AU, Correia MAR. 2015. Boron foliar application in nutrition and yield of beet and tomato. J Plant Nutr. 38(10):1573–1579. doi:10.1080/01904167.2015.1043373.

Harish Sundaramooorthy S, Kumar D, Vajiapurkar SG, Vajiapurkar SG. 2008. A new chlorophylceous nickel hyperaccumulator. Bioreosour Technol. 99(9):3930–3934. doi:10.1016/j.biortech.2007.07.043.

Hawksford M, Horst W, Kichey T, Lambers H, Schojerring J, Moller SI, White P. 2012. Functions of macronutrients. In: Marschner P, editor. Marschner’s mineral nutrition of higher plants. New York: Elsevier; p. 135–189.

Ho LC, White PJ (2005) A cellular hypothesis for the induction of blossom-end rot in tomato fruit. Ann. Bot. 95:571–581

Hoagland DR, Arnon DI. 1950. The water culture method for growing plants without soils. Berkeley (CA): California Agricultural Experimental Station.

Kaur C, Ghosh A, Pareek A, Singla-Pareek SL. 2014. Glyoxalases and stress tolerance in plants. Biochem Soc Trans. 42(2):485–490. doi:10.1042/BST20130242.

Küpper H, Lambi E, Zhao FJ, Wieshammer G, McGrath SP. 2001. Cellular compartmentation of nickel in the hyperaccumulators Alyssum lesbiacum, Alyssum bertolonii, and Thlaspi goesingense. J Exp Bot. 52(365):2291–2300. doi:10.1093/jexbot/52.365.2291.

Kutman BY, Kutman UB, Cakman I. 2013. Foliar nickel application alleviates detrimental effects of glyphosate drift on yield and seed quality of wheat. J Agric Food Chem. 61(35):8364–8372. doi:10.1021/jf402194v.

Macedo FG, Bresolin JD, Santos EF, Furlan F, Silva WTL, Polacco JC, Lavres J. 2016. Nickel availability in soil as influenced by liming and its role in soybean nitrogen metabolism. Front Plant Sci. 7:1358. doi:10.3389/fpls.2016.01358.

Macedo FG, Montanha GS, Carvalho HWP, Melo WJ. 2021. Nickel influences urease activity and calcium distribution in tomato fruits. ACS Agric Sci Technol. 1(1):29–34. doi:10.1021/acsagscitech.0c00003.

Malavolta E, Leão HC, Oliveira SC, Lavres J Jr, Moraes MF, Cabral CP, Malavolta M. 2006. Repartition of nutrients in citrus flowers, leaves and branches. R Bras Frutic. 28(3):506–511. doi:10.1590/S0100-29452006000300036.

Miller RO. 1998. Nitric-perchloric acid wet digestion in an open vessel. In: Karla YP, editor. Handbook of reference methods for plant analysis. Boca Raton (FL): CRC Press; p. 57–61.

Mohseni R, Ghaderian SM, Schat H. 2019. Nickel uptake mechanisms in two Iranian nickel hyperaccumulators, Odontanthera bracteata and Odontanthera inflata. Plant Soil. 434(1–2):263–269. doi:10.1007/s11104-018-3814-3.

Mustafiz A, Ghosh A, Tripathi AK, Kaur C, Ganguly AK, Bhaves NS, Tripathi JK, Pareek A, Sopory SK, Singla-Pareek SL. 2014. A unique Ni2+-dependent and methylglyoxal-inducible rice glyoxalase I possesses a single active site and functions in abiotic stress response. Plant J. 52(6):951–963. doi:10.1111/tpj.12521.

Nonami H, Fukuyama T, Yamamoto M (1995) Blossom-end rot of tomato plants may not be directly caused by calcium deficiency. Acta Hortic 396:107–114

Paiva HN, Carvalho JG, Siqueira JO. 2003. Effect of the increasing levels of nickel on the nutrients content and accumulation in ipé-roxo (Tabebuia impetiginosa (Mart.) Standley) seedlings. Sci For. 63:158–166.

Palacios G, Gomez J, Ccbronell-Barrachuma A, Pedreno JN, Mataix J. 1998. Effect of nickel on concentration on tomato plant nutrition and dry matter yield. J Plant Nutr. 21(10):2179–2191. doi:10.1080/01904169809365553.
Petersen, KK, Willumsen, J. (1992). Effects of root zone warming and season on blossom-end rot and chemical composition of tomato fruit. Tidsskr. Planteavl. 96: 489–498
Raij B, Cantarella H, Quaggio JA, Furlani AMC. 1997. Recomendações de adubação e calagem para o Estado de São Paulo. 2nd ed. Campinas: Instituto Agronômico de Campinas (Boletim técnico, 100).
Roach WA, Barclay C. 1946. Nickel and multiple trace deficiencies in agricultural crops. Nature. 157(3995):696. doi:10.1038/157696a0.
SAS Institute. 1996. SAS/STAT. User’s guide, version 6.11. 4.ed. Cary. Stat Anal Syst Inst. 2:842.
Sreekanth TVM, Nagajyothi PC, Lee KD, Prasad TNVK. 2013. Occurrence, physiological responses and toxicity of nickel in plants. Int J Environ Sci Technol. 10(5):1129–1140. doi:10.1007/s13762-013-0245-9.
Suzuki K, Shono M, Egawa Y. 2003. Localization of calcium in the pericarp cells of tomato fruits during the development of blossom-end rot. Protoplasma. 222(3–4):149–156. doi:10.1007/s00709-003-0018-2.
Tiwari M, Sharma NC, Fleischmann P, Burbage J, Venkatachalam P, Sahi SV. 2017. Nanotitania exposure causes alterations in physiological, nutritional and stress responses in tomato (Solanum lycopersicum). Front Plant Sci. 8:633. doi:10.3389/fpls.2017.00633.
Williams M. 2015. “Plant Nutrition: Micronutrients and metals.” The Plant Cell vol. 27,5 (2015). doi:10.1105/tpc.115. tt0515.
Wissemeier AH, Zuhlke G. 2002. Relation between climatic variables, growth and the incidence of tipburn in field-grown lettuce as evaluated by simple, partial and multiple regression analysis. Sci Hortic. 93(3–4):193–204. doi:10.1016/S0304-4238(01)00339-9.