Photosynthetic Parameters and Growth of Rice, Lettuce, Sunflower and Tomato in an Entisol as Affected by Soil Acidity and Bioaccumulation of Ba, Cd, Cu, Ni, and Zn

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Abstract
The bioaccumulation of trace elements (TEs) in crops consumed by humans can reduce food production as a consequence of photosynthetic damage in plants and cause several diseases in humans. Liming is a soil management strategy designed to alleviate soil acidity and mitigating these problems by reducing the TE bioavailability. In this study, we evaluated the effect of liming on photosynthesis, growth, and bioaccumulation of barium (Ba), cadmium (Cd), copper (Cu), nickel (Ni), or zinc (Zn) in lettuce (Lactuca sativa L.), rice (Oryza sativa L.), sunflower (Helianthus annuus L.), and tomato (Solanum lycopersicum L.) grown in a sandy Entisol. The crops were grown in either uncontaminated or contaminated Entisol, at two base saturation (BS%) ratios: 30% for all crops or 50% for rice and 70% for lettuce, sunflower, and tomato. The photosynthesis-related parameters varied depending on the metal and the crop, but in general, increasing BS% did not attenuate photosynthetic damage induced by Ba, Cd, Cu, Ni, and Zn in the crops. There was no strong correlation between the photosynthetic parameters and biomass production, which indicates that the suppression of biomass induced by Ba, Cd, Cu, Ni, or Zn is related to other metabolic disorders in addition to the impairment of CO2 assimilation or chlorophyll synthesis in the crops assayed, with the exception of Ni and Zn in lettuce. In conclusion, increasing BS% was not consistent in reducing Ba, Cd, Cu, Ni, and Zn accumulation in the edible parts of lettuce, rice, sunflower, and tomato grown in the sandy soil, which is probably related to the low capacity of this soil to control TE bioavailability.

Trace elements (TEs) are minor components in the solid soil phase, but they play an important role in soil fertility, soil contamination, and food production (Gupta et al. 2019). Elements, such as barium (Ba), cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn), are frequently present in low concentrations (Kabata-Pendias 2011). However, the increasing soil contamination with these elements through anthropogenic activities, such as mining, have become a global issue and environmental threat, because these TEs can be accumulated in plant tissues and enter the food chain (Jolly et al. 2013).

Crops, such as lettuce (Lactuca sativa L.), rice (Oryza sativa L.), sunflower (Helianthus annuus L.), and tomato (Solanum lycopersicum L.), are amongst the most commonly consumed foods in the world. These crops can accumulate TEs in their edible parts in concentrations sufficient to cause clinical problems to humans (Piotto et al. 2018; Gupta et al. 2019; Lavres et al. 2011, 2019). Nervous, cardiovascular, renal, and neurological impairment, as well as bone diseases caused by Ba, Cd, Cu, Ni, and Zn have been reported in humans (Tchounwou et al. 2012; Petrosino et al. 2018).

Cadmium, Cu, Ni, and Zn are some of the most important elements in the context of environmental pollution (He et al. 2015), whereas Ba has frequently been detected at concentrations above what is considered safe for the environment and humans in Brazil (Tavares et al. 2015). Given this scenario, the employment of strategies that mitigate these TE uptakes by crops consumed in abundance by humans is somewhat important to reducing their intake. Plants can take up only bioavailable TEs from the soil. This process depends on the uptake mechanisms, physico-chemical properties of the soil and chemical speciation of
the metals and metalloids in the soils (Gupta et al. 2019). Thus, agricultural practices that influence TE bioavailability often have an impact on their accumulation in plants.

Lime often is used to correct soil acidity and allow for adequate crop development (Raij et al. 1996). The higher pH and soil base saturation (BS) in limed soils tend to increase sorption and decrease the bioavailability and mobility of most TEs in soils (Rieuwerts 2007). Macedo et al. (2020) evaluated the effect of two BS ratios (50% and 70%) on sunflower and soybean (Glycine max L.) growth in an Alfisol and observed that Ni bioavailability was lower, and the biomass production was higher at BS of 70% compared to 50%.

Although liming decreases the TE bioavailability (Macedo et al. 2020), certain crops can accumulate more TEs than others in the same soil condition due to their physiological mechanisms. Melo et al. (2014) described that sorghum (Sorghum bicolor L.) and maize (Zea mays L.) accumulated more Ba and Cd than soybean and pea (Pisum sativum L.) when these crops were grown under the same conditions in an Oxisol and an Entisol. Nevertheless, the pH rise resulted from liming is an effective strategy for decreasing TE uptake by crops consumed by humans. Li et al. (2019) measured, through bioconcentration factor (BCF) and translocation factor (TF), the Cd transfer from soils to rice in China and reported that Cd translocation to the grains of rice plants grown in soils that presented higher pH values (which correspond to higher BS) was lower. According to Li et al. (2019), soil properties were highly relevant to Cd accumulation in rice plants.

The accumulation of certain TEs in plants causes toxic effects on plant growth, even in low concentrations (Hänisch and Mendel 2009). Physiological effects of TE toxicity on plants include reductions in biomass, changes in photosynthetic efficiency, and transpiration (Gupta et al. 2019). Changes in chlorophyll synthesis and starch accumulation also have been reported in plants exposed to different TEs (Moya et al. 1993; Piotto et al. 2018; Lavres et al. 2019). Given this background, a lower TE uptake and translocation of Ba, Cd, Cu, Ni, and Zn in the crops can affect the photosynthetic process and, consequently, biomass production. Thus, this study offers a scientific base for a rational choice of which crop may be cultivated in each condition of Entisol pollution by TEs. Thus, our goals with this study were to evaluate: (1) the effect of BS on changes induced by TEs on chlorophyll concentration, leaf CO2 assimilation, stomatal conductance, intracellular CO2 concentration, and transpiration, and growth of lettuce, rice, sunflower, and tomato grown in Ba, Cd, Cu, Ni, or Zn-contaminated Entisol; and (2) the uptake and root-to-shoot translocation of Ba, Cd, Cu, Ni, and Zn in the crops.

### Material and Methods

#### Soil Characterization

The soil (Typic Quatzipsamment) used in this study was collected from the upper layer (0.0–0.2 m depth), apart from litter, in São Pedro, in the state of São Paulo, Brazil (22°32’ S; 47°54’ W). Soil characteristics were determined on air-dried soil sieved with a 2-mm mesh (Table 1), following the procedures described by Nelson and Sommer (1982) to determine OC content, after digestion with K2Cr2O7 and H2SO4. Exchangeable aluminum (Al3+) was extracted with 1 mol L−1 KCl and determined by titration with 0.025 mol

| Element | Concentration (mg kg⁻¹) |
|---------|-------------------------|
| Ba      | 3.6                     |
| Cd      | 0.8                     |
| Cu      | 15.2                    |
| Ni      | 2.2                     |
| Zn      | 14.5                    |

Table 1 Descriptive analysis of some chemical and physical properties of the Entisol used in this study

| Element | Concentration (mg kg⁻¹) |
|---------|-------------------------|
| Ba      | 3.6                     |
| Cd      | 0.8                     |
| Cu      | 15.2                    |
| Ni      | 2.2                     |
| Zn      | 14.5                    |

The concentrations of trace elements evaluated in this study are highlighted in bold

SB sum of bases; CEC7.0 Cation Exchange Capacity at pH 7.0; BS base saturation; m saturation by aluminum; OC organic carbon
L⁻¹ NaOH (Raij et al. 2001). The pH was determined first in 0.01 mol L⁻¹ CaCl₂ and then in SMP solution to estimate the potential acidity (H⁺ + Al) (Raij et al. 2001). The available concentrations of Ca, Mg, K, and P were extracted with ionic exchange resin (Raij et al. 1986).

From these results we next calculated the sum of bases (SB), total cationic exchange capacity (CEC), base saturation (BS%), and Al³⁺ saturation (m%) (EMBRAPA 1997). The pseudo-total Ba, Cd, Cu, Ni, and Zn concentrations were determined using the 3051A method (digestion in a closed microwave oven system with concentrated HNO₃ and HCl (3:1) proposed by the United States Environmental Protection Agency—USEPA (USEPA 2007). Granulometric fractions (sand, silt, and clay) were obtained by the hydrometer method (Gee and Bauder 2002).

### Plant material and Experimental Design

To assay the effect of BS on plant growth and Ba, Cd, Cu, Ni, and Zn uptake by crops ingested by humans, plants of lettuce (cv. Amanda), rice (cv. IAC-202), sunflower (cv. Aguará 4), and tomato (cv. Santa Clara VF 5600) were grown in greenhouse conditions in unpolluted (control treatment) or polluted Entisol, under two BS (30% for all crops or 50% for rice and 70% for lettuce, sunflower, and tomato). The original BS of the Entisol (Table 1) was increased to 30% for all crops or to 50% for rice and 70% for lettuce, sunflower, and tomato. The plant material collected was dried in a forced ventilation oven at 45 °C to constant weight only into roots and shoot. The plant material collected was dried in a forced ventilation oven at 45 °C to constant weight

The soil was incubated in this condition for 21 days, at maximum temperature of 31 °C. After this incubation period, Ba, Cd, Cu, Ni, or Zn solutions were added in the following concentrations: 120 mg Ba kg⁻¹ [Ba(NO₃)₂₂], 1.3 mg Cd kg⁻¹ [Cd(NO₃)₂.4H₂O], 60 mg Cu kg⁻¹ [Cu(NO₃)₂.3H₂O], 30 mg Ni kg⁻¹ [Ni(NO₃)₂.6H₂O], and 86 mg Zn kg⁻¹ [Zn(NO₃)₂.6H₂O]. Variations in N supply were corrected by using NH₄NO₃, including the unpolluted Entisol (control treatment). Next, the soil was incubated again for 7 days at 95% of their maximum water-holding capacity.

After soil incubation, lettuce and tomato seedlings were sown in vermiculite and then transferred to pots at 29 and 34 days after sowing, respectively. Rice and sunflower were sown directly in the pots. One plant of sunflower and tomato was kept in each pot, whereas three plants of lettuce and five plants of rice were kept in each pot. Soil moisture content was maintained at a constant level (70% of the maximum water holding capacity) during the study, with deionized water.

All crops received basic fertilization in applications of 90 mg of N kg⁻¹, 200 mg of P kg⁻¹, 50 mg of K kg⁻¹, 23.2 mg of S kg⁻¹, 1 mg of B kg⁻¹, 5 mg of Cl kg⁻¹, 1 mg of Cu kg⁻¹, 5 mg of Mn kg⁻¹, and 3 mg of Zn kg⁻¹, following the recommendations of Raij et al. (1996). Copper and Zn were not applied to Cu- and Zn-polluted soils. Fifteen days after sowing, some of the nutrients were top-dressed: lettuce, sunflower, and tomato received 50 mg of K kg⁻¹ and 20.5 mg of S kg⁻¹, whereas the same fertilization was applied to rice, 20 days after sowing. A new fertilization with 50 mg of N kg⁻¹ and 50 mg of K kg⁻¹ was applied at 48 days after rice, sunflower, and tomato sowing (Raij et al. 1996).

We applied 28.2 mL of ha⁻¹ of thiamethoxam and 21.2 mL of ha⁻¹ of lambda-cyhalothrin following the first top fertilization to control the caterpillar pest Trichoplusia ni. that was found in the leaves of all crops during the study. The powdery mildew (Microsphaera diffusa) was controlled in rice and sunflower plants through two applications of 250 g of ha⁻¹ of carbendazim on their leaves (the first application occurred after the first top fertilization, and the second was applied after the second top fertilization).

Lettuce plants were harvested at 42 days after transplanting (end of vegetative phase), whereas rice was harvested at 98 days after sowing (phenological reproductive stage R8). Sunflower was harvested at 82 days after sowing (phenological reproductive stage R9), and tomato was harvested at 68 days after transplanting (after the harvesting of mature fruits). Plants were harvested and separated into roots, shoot, and fruits or grains (except for lettuce that was separated only into roots and shoot). The plant material collected was dried in a forced ventilation oven at 45 °C to constant weight.
to determine the biomass production. The soil collected at
the end of the study was sieved (2-mm mesh) and dried in
a forced ventilation oven at 45 °C to determine the pseudo-
total Ba, Cd, Cu, Ni, and Zn concentrations.

Determination of the Pseudo-Total Ba, Cd, Cu, Ni,
and Zn Concentrations in the Entisol

The term pseudo-total is normally used in soil studies and
theoretically refers to the total concentration of a certain
element in the soil, regardless of whether the fractions are
available for plant uptake (USEPA 2007; CETESB 2014).
Pseudo-total concentrations were determined in triplicate
after microwave-assisted analysis (Model TC plus labsta-
tion, Milestone, Sorisole, Italy) according to the USEPA
3051A method (USEPA 2007). Extracts were analyzed by
inductively coupled plasma optical emission spectroscopy
(ICP-OES, iCAP 7000 SERIES, Thermo Fisher Scientific,
Waltham, USA). Blank reagent samples and standard refer-
ence material (SRM 2709a—San Joaquin soil) were used
during digestion for quality control.

Determination of Ba, Cd, Cu, Ni, and Zn
Concentrations and Contents in the Plant Material

After drying in an oven at 45 °C until reaching constant
weight, the plant material was ground in a Wiley type
mill (Model 4, Thomas Scientific, Swedesboro, USA) and
digested in a microwave (Model TC plus labstation, Mile-
stone) oven using a mixture of HNO3 + H2O2, following the
USEPA 3051A method (USEPA 2007) for TE determina-
tion by inductively coupled plasma optical emission spec-
trometry (ICP-OES, iCAP 7000 SERIES, Thermo Fisher Scientific).

Blank reagent samples were used in digestion for qual-
ity control. Standard reference material (SRM1515—apple
leaves) also was used to ensure the accuracy and precision
of the analytical methods. Next, from the TE concentrations,
we calculated the TE content by multiplying the TE concen-
tration in the tissue (roots, shoot and grains or fruits) by the
dry weight of the respective tissue. Subsequently, the TE
content in each tissue was added, resulting in the total TE
content (roots + shoot + grains or fruits).

Calculation of BCF and TF for Ba, Cd, Cu, Ni, and Zn

The transfer of TEs in the crop tissues was evaluated by two
indicators (Antoniadis et al. 2017): (1) the bioconcentra-
tion factor (BCF), which indicates the efficiency of a plant
species in accumulating a TE into its tissues from the soil
(Eq. 1), and (2) the translocation factor (TF), which indicates
the plant capacity to translocate TEs from roots to the aerial
parts (Eq. 2):

\[
BCF = \frac{[\text{TE}_{\text{crop}}]}{[\text{TE}_{\text{soil}}]} \tag{1}
\]

where: \([\text{TE}_{\text{crop}}]\) (mg kg\(^{-1}\) DW) is the TE concentration in the
roots, shoot and grains or fruits of the plants, and \([\text{TE}_{\text{soil}}]\)
(mg kg\(^{-1}\) soil), the pseudo-total TE concentration in the soil.

\[
TF = \frac{[\text{TE}_{\text{shoot}}]}{[\text{TE}_{\text{roots}}]} \tag{2}
\]

where: \([\text{TE}_{\text{shoot}}]\) (mg kg\(^{-1}\) DW) is the TE concentration in the
shoot (stem + leaves + grains or fruits), and \([\text{TE}_{\text{roots}}]\) (mg
kg\(^{-1}\) DW), the TE concentration in the roots.

Determination of the Photosynthetic Parameters
in the Crops Assayed

Leaf area was determined in a leaf area integrator model
LI 3100 (Li-Cor Inc., Lincoln, USA) at the moment of
the plant harvest. Chlorophyll concentration was measured
during the vegetative phase (at 17 and 18 days after lettuce
and tomato transplanting, respectively, and at 14 days after
rice and sunflower emergence) by a Chlorophyll Meter SPAD-
502 (Soil–Plant Analysis Dev., Section, Minolta Camera Co.,
Osaka, Japan). Chlorophyll concentrations as well as the fol-
lowing photosynthetic parameters were measured in the first
fully expanded leaf of lettuce and rice, and in the second pair
of leaves from above to the top of the sunflower and tomato.

Photosynthetic parameters [leaf CO\(_2\) assimilation (A),
stomatal conductance (g\(_s\)), intracellular CO\(_2\) concentration
(C\(_i\)), and transpiration (E)] were measured using infrared
gas analyzer (Li-6400, Li-cor Inc.) before the plant har-
vest. The parameters were measured at air CO\(_2\) concentra-
tion of 350 μmol mol\(^{-1}\) with a photosynthetic photon
flux density of 1,000 μmol m\(^{-2}\) s\(^{-1}\) for lettuce and rice and
2,000 μmol m\(^{-2}\) s\(^{-1}\) for sunflower. All measurements were
performed following the recommendations of Long and Bern-
cachi (2003). The photosynthetic measurements described
(except for chlorophyll concentration) were not performed
on tomato plants due to the beginning of the leaf senescence
process at the moment of the plant harvest.

Statistical Analyses

Both normality and homoscedasticity were checked. Next, all
data were submitted to analysis of variance (F test) and post-
hoc Tukey test (\(P \leq 0.05\)) through the Statistical Analysis Sys-
tem v. 9.2 (SAS Institute 2008). The graphs were constructed
and plotted using SigmaPlot v. 10.0 (Systat Software Inc., San
Jose, CA). Results were expressed as mean ± standard error
of the mean.
Results

Effect of Base Saturation on Pseudo-Total Ba, Cd, Cu, Ni, and Zn Concentrations in the Entisol

In general, there was no effect of BS on pseudo-total Ba, Cd, Cu, Ni, and Zn concentrations in the polluted Entisol, with a few exceptions (Fig. 1). The pseudo-total Ba concentration in the Entisol cultivated with lettuce was 20% lower at BS of 70% compared with 30% (Fig. 1A). The increase in BS also resulted in a reduction of 28% in the pseudo-total Cu concentration in the Entisol cultivated with rice (Fig. 1C). On the other hand, there was an increase of 13 and 14% in the pseudo-total Cd concentration in the Entisol cultivated with rice and sunflower, respectively, when the BS was augmented (Fig. 1B).

Fig. 1 Pseudo-total concentrations of Ba (A), Cd (B), Cu (C), Ni (D) and Zn in unpolluted (control treatment) or Ba, Cd, Cu, Ni or Zn-polluted Entisol cultivated with lettuce, rice, sunflower or tomato under two soil base saturation (BS%). Distinct upper case letters indicate difference between base saturation within each crop for each condition (unpolluted or polluted Entisol) and distinct lower case letters indicate difference between unpolluted or polluted Entisol within each base saturation for each crop (Tukey test, \( P \leq 0.05 \)). The dash line (in red) indicates the trace elements concentrations corresponding to the prevention levels established by The São Paulo State Environmental Agency—CETESB, in Brazil (CETESB 2014)
The same occurred for the pseudo-total Zn concentration that was 55% and 23% higher in the Entisol cultivated with rice and sunflower, respectively, at the highest BS (Fig. 1E). However, in general, Ba, Cd, Cu, Ni, and Zn bioavailability decreased due to the increase in BS (results not shown). Details about the TE bioavailability can be found in Pinto and Alleoni (2018).

**Effect of BS and Ba, Cd, Cu, Ni, and Zn Exposure on Biomass and Photosynthesis**

Lettuce plants had higher shoot biomass when grown at BS of 70%, regardless of TE exposure (Fig. 2B). However, there was no effect of BS on root biomass, except for lettuce plants grown on Cu-polluted Entisol that presented higher root biomass at BS of 70% (Fig. 2C). Lettuce plants grown at BS of 30% were more susceptible to Cu, Ni, and Zn toxicity, but the increase in BS to 70% decreased the Cu-induced toxicity compared with the other TEs (Figs. 2B-C).

There was a positive effect of increasing BS on rice grain production though only for plants exposed to Cd or Zn (Fig. 2D). Meanwhile, rice growth and grain production were more compromised by the Cu-induced toxicity compared to the other TEs (Figs. 2D-F). In general, sunflower plants grown at BS of 70% presented higher grain production (Fig. 2G), shoot (Fig. 2H), and root biomass (Fig. 2I) compared with plants grown at BS of 30%. Sunflower was more susceptible to toxicity induced by Ni and Zn compared with the other TEs, especially when the plants were grown at the lowest BS (Figs. 2G-I).

There was no effect of BS on tomato fruit production, with the exception of plants exposed to Ni that had higher fruit production at BS of 70% (Fig. 2J). On the other hand, shoot and root biomass of tomato plants exposed to all TEs was higher at BS of 70% (Figs. 2K-L). Tomato plants were more susceptible to Ni-induced toxicity, followed by Cd, Cu, and Zn, especially when grown at BS of 30% (Figs. 2L).

In addition to decreases in biomass, TEs can induce significant damage in photosynthesis-related plant parameters. Lettuce was more susceptible to Cu-induced inhibition of the leaf area and transpiration when grown at BS of 30% compared with 70% (Table 2). However, Cd, Ni, and Zn
| Parameters | Leaf area (cm²/pot) | Chlorophyll (SPAD units) | $A$ (µmol CO₂ m⁻² s⁻¹) | $g_s$ (mol H₂O m⁻² s⁻¹) | $g_C$ (µmol CO₂ mol⁻¹) | $E$ (mmol m⁻² s⁻¹) |
|------------|---------------------|--------------------------|-------------------------|----------------------|-----------------------|---------------------|
| Lettuce    |                     |                          |                         |                      |                       |                     |
| Control    | 853 ± 60 Aa          | 1032 ± 100 Aa            | 14.9 ± 1.9              | 10.98 ± 0.22         | 0.33 ± 0.09           | 11.27 ± 0.78        |
| Ba         | 1032 ± 99 Aa         | 1142 ± 233 Aa            | 14.8 ± 0.7              | 9.26 ± 0.12          | 0.09 ± 0.02           | 5.16 ± 0.40         |
| Cd         | 971 ± 91 Aa          | 1106 ± 152 Aa            | 12.4 ± 0.6              | 12.25 ± 2.25         | 0.05 ± 0.00           | 8.76 ± 1.22         |
| Cu         | 300 ± 38 Bb          | 1285 ± 147 Aa            | 16.4 ± 1.5              | 11.09 ± 3.54         | 0.36 ± 0.04           | 1.36 ± 0.19         |
| Ni         | 188 ± 21 Bb          | 500 ± 29 Ab              | 11.7 ± 1.9              | 2.23 ± 0.35          | 0.03 ± 0.00           | 0.81 ± 0.10         |
| Zn         | 196 ± 29 Ab          | 206 ± 39 Ab              | 12.4 ± 0.7              | 2.47 ± 0.50          | 0.02 ± 0.00           | 1.69 ± 0.86         |
| Rice       |                     |                          |                         |                      |                       |                     |
| Control    | 2861 ± 142 Aa        | 3134 ± 58 Aa             | 36.7 ± 0.3              | 12.22 ± 2.59         | 0.11 ± 0.02           | 1.40 ± 0.02         |
| Ba         | 3328 ± 136 Aa        | 3114 ± 63 Aa             | 36.5 ± 0.6              | 16.18 ± 0.86         | 0.20 ± 0.05           | 4.97 ± 0.36         |
| Cd         | 2994 ± 73 Aa         | 3479 ± 25 Aa             | 35.5 ± 0.6              | 15.69 ± 0.34         | 0.17 ± 0.00           | 3.22 ± 0.24         |
| Cu         | 2159 ± 449 Bb        | *                        | 31.7 ± 2.8 a            | *                    | 0.21 ± 0.03           | 4.09 ± 0.61         |
| Ni         | 2704 ± 119 Aa        | 3061 ± 33 Aa             | 32.9 ± 1.3              | 8.56 ± 0.42          | 0.18 ± 0.03           | 2.56 ± 0.20         |
| Zn         | 3359 ± 255 Aa        | 3173 ± 238 Aa            | 35.2 ± 0.6              | 12.36 ± 0.66         | 0.18 ± 0.03           | 4.29 ± 0.47         |
| Sunflower  |                     |                          |                         |                      |                       |                     |
| Control    | 3213 ± 459 Aa        | 3816 ± 405 Aa            | 31.2 ± 0.5              | 23.17 ± 2.18         | 0.13 ± 0.13           | 3.94 ± 0.00         |
| Ba         | 2948 ± 515 Aa        | 3990 ± 284 Aa            | 34.0 ± 0.1              | 25.20 ± 3.44         | 0.09 ± 0.06           | 3.00 ± 1.15         |
| Cd         | 2096 ± 573 Bab       | 4188 ± 366 Aa            | 30.3 ± 1.8              | 21.94 ± 3.95         | 0.70 ± 0.18           | 5.52 ± 1.95         |
| Cu         | 2345 ± 7 Aa          | 2085 ± 337 Aa            | 31.7 ± 6.5              | 23.22 ± 6.02         | 0.11 ± 0.00           | 9.86 ± 0.37         |
| Ni         | 1757 ± 335 b         | *                        | 33.9 ± 0.9 a            | *                    | 0.54 ± 0.23           | 6.93 ± 1.94        |
Table 2 (continued)

| Crop | 30% | 70% | 30% | 70% | 30% | 70% | 30% | 70% | 30% | 70% | 30% | 70% | 30% | 70% |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Sunflower | | | | | | | | | | | | | | |
| Zn | 1879 ± 197 Ab | 3314 ± 120 Aa | 21.2 ± 1.2 Bb | 28.0 ± 0.5 Aa | 27.15 ± 0.01 Aab | 25.89 ± 2.93 Aa | 0.38 ± 0.04 Aa | 0.62 ± 0.21 Aa | 196 ± 14 Aa | 238 ± 56 Aab | 4.23 ± 1.11 Bbc | 8.25 ± 1.96 Aa |
| Tomato | | | | | | | | | | | | | | |
| Control | – | – | – | – | – | – | – | – | – | – | – | – | – | – |
| Ba | – | – | 39.7 ± 1.7 Aa | 40.9 ± 1.6 Aa | – | – | – | – | – | – | – | – | – | – |
| Cd | – | – | 38.4 ± 4.0 Aa | 36.5 ± 1.5 Aa | – | – | – | – | – | – | – | – | – | – |
| Cu | – | – | 45.5 ± 4.2 Aa | 43.4 ± 3.6 Aa | – | – | – | – | – | – | – | – | – | – |
| Ni | – | – | 49.3 ± 2.2 Aa | 45.8 ± 1.2 Aa | – | – | – | – | – | – | – | – | – | – |
| Zn | – | – | 37.3 ± 6.0 Aa | 42.8 ± 0.6 Aa | – | – | – | – | – | – | – | – | – | – |

Means followed by distinct upper case letters indicate difference between base saturation within each condition (Control = unpolluted, or Ba-, Cd-, Cu-, Ni-, or Zn-polluted Entisol) for each crop, and distinct lower case letters indicate difference between each condition (Control = unpolluted, or Ba-, Cd-, Cu-, Ni-, or Zn-polluted Entisol) within each base saturation for each crop (Tukey test, P ≤ 0.05).

Asterisks (*) indicate treatment lost due to plant death.
exposure decreased the chlorophyll concentration of lettuce more compared to Cu, regardless of BS. The leaf CO₂ assimilation and stomatal conductance in lettuce was compromised especially by Ni and Zn, regardless of BS.

In general, there was no effect of BS on photosynthetic parameters measured in rice, as well as there were no notable changes induced by the different TEs on leaf area, chlorophyll concentration, stomatal conductance, intracellular CO₂ concentration, and transpiration of rice grown at BS of 50% (Table 2). Nevertheless, there was Ni-induced inhibition on leaf CO₂ assimilation of rice grown at BS of 50%. There was an increase in chlorophyll concentration and transpiration induced by the higher BS in sunflower exposed to Zn, which also was observed for leaf CO₂ assimilation, stomatal conductance, intracellular CO₂ concentration, and transpiration of sunflower exposed to Ba. Despite the biomass of sunflower having been reduced by Ni and Zn (Figs. 2G-I), these TEs did not induce severe photosynthetic damages, which suggest to us that Ni and Zn toxicity in sunflower is related to other processes. Chlorophyll concentration in tomato was not affected by BS or TE exposure.

**Effect of BS on Uptake and Transfer of Ba, Cd, Cu, Ni, and Zn to Edible Parts of Crops**

The concentrations of the TEs in the edible parts of lettuce, rice, sunflower, and tomato grown on unpolluted Entisol remained below the maximum levels permitted by International Organizations, regardless of BS (data not shown). The Food and Agriculture Organization of the United Nations (FAO) for the World Health Organization (WHO) have established threshold values of 0.2 mg kg⁻¹ DW for Cd, 40 mg kg⁻¹ DW for Cu, and 60 mg kg⁻¹ DW for Zn (FAO and WHO 2011). In the case of Ba and Ni, neither the FAO nor the WHO have established threshold values, but the Environmental Protection Agency’s Integrated Risk Information System (EPA-IRIS) has established 0.3 mg kg⁻¹ DW for Ba and Ni (EPA-IRIS 1987a,b). Thus, from this point on, our focus was directed at understanding the effect of BS on uptake and translocation of Ba, Cd, Cu, Ni, and Zn in the crops grown in the polluted Entisol (Figs. 3 and 4).

Barium, Cd, and Ni concentrations recorded in the edible parts of all crops grown on polluted Entisol exceeded the

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**Fig. 3** Concentrations of Ba (A-C), Cd (E–G), Cu (I–K), Ni (M–O) and Zn (Q–S) in fruits or grains (A, E, I, M and Q), shoot (B, F, J, N and R) and roots (C, G, K, O and S) and total content of Ba (D), Cd (H), Cu (L), Ni (P) and Zn (T) in lettuce, rice, sunflower and tomato grown on Ba, Cd, Cu, Ni or Zn-polluted Entisol under two soil base saturation (BS%). Distinct upper case letters indicate difference between base saturation within each crop for each trace element and distinct lower case letters indicate difference between each trace element within each base saturation for each crop (Tukey test, \( P \leq 0.05 \)). Asterisks (*) indicate treatment lost due to plant death. ND=non-detected.
maximum permitted levels described (Figs. 3A-B, 3E-F, and 3M-N). Only lettuce grown on Cu-polluted Entisol at BS of 30% exceeded the maximum permitted levels for Cu in its edible part (Figs. 3I-J). Zinc concentration in the edible parts of lettuce and sunflower grown on Zn-polluted Entisol also exceeded the maximum permitted levels for Zn (FAO and WHO 2011), regardless of BS (Figs. 3Q-R).

Although lettuce had presented shoot Cu concentration below the maximum permitted levels for Cu when grown in the Cu-polluted Entisol at base soil saturation of 70%, there was no significant effect of BS on Ba, Cd, Cu, Ni, and Zn concentrations in shoot or roots (Figs. 3A-C, 3E-G, 3I-K, 3M-N, and 3Q-R). There also was no effect of BS on Ba, Cd, Cu and Ni concentrations in the grains, shoot, or roots of rice plants (Figs. 3A-C, 3E-G, 3I-K, and 3M-N). However, Zn concentrations in the grains and roots of rice were lower at BS of 50% compared with 30% (Figs. 3Q and 3S).

In general, sunflower tissues had higher Ba concentrations and lower Zn concentrations when this plant was grown at the highest BS (Figs. 3B-C and 3Q-R). There was no effect of BS on Cd, Cu, and Ni concentrations in the grains, shoot, or roots of sunflower plants (Figs. 3E-G, 3I-K, and 3Q-S). Tomato plants grown at BS of 70% presented lower Ba and Zn concentrations in its roots (Figs. 3C and 3S). Meanwhile, there was no effect of BS on Cd, Cu and Ni concentrations in the fruits, shoots, or roots of tomatoes (Figs. 3E-G, 3I-K and 3Q-S).

Sunflower plants had higher Ba (Fig. 3A), Cd (Fig. 3E), Cu (Fig. 3I), Ni (Fig. 3M), and Zn (Fig. 3Q) concentrations in their grains compared with rice grains and tomato fruit when the plants were grown at the highest BS. On the other hand, lettuce had higher Ni (Fig. 3N) and Zn (Fig. 3R) concentrations in its leaves compared with the other crops grown at the highest BS.

Higher TE concentrations were found in the roots for all crops, followed by shoot and grains or fruit, respectively (Fig. 3). There was no effect of BS on Cd (Fig. 3H), Cu (Fig. 3J), and Ni (Fig. 3P) contents. However, sunflower and rice presented higher Ba content (Fig. 3D), whilst lettuce, sunflower, and tomato had higher Zn content.
(Fig. 3T) at the highest BS compared with 30%, which can be attributed to the higher biomass production at the highest BS. Taking the TE contents (Figs. 3D, 3H, 3L, 3P, and 3T) into account, the crops assayed absorbed TEs from the polluted Entisol in the following order: lettuce, Ba = Zn > Cu = Ni > Cd; rice, Zn > Ba > Ni > Cu > Cd; sunflower, Ba > Zn > Cu > Ni > Cd; and tomato, Ba = Zn > Ni > Cu > Cd.

The higher TE concentrations observed in the roots compared to shoot and grains or fruits (Fig. 3) were directly associated with the BCF and TF values recorded in this study (Fig. 4). All crops presented higher BCF in the roots, followed by shoot and grains or fruit, respectively (Figs. 4A-C, 4E-G, 4I-K, 4M-O, and 4Q-S). There was an effect of BS on BCF and TF values in only a few cases. Lettuce plants grown at BS of 70% presented lower BCF for Cd and Ni in its shoot compared with BS of 30% (Figs. 4F and 4N). The lower Ni BCF in the shoot was closely related to the lower Ni TF observed in lettuce grown at BS of 70% (Fig. 4P).

Increasing BS to grow rice resulted in lower Zn BCF in the whole plant (Figs. 4Q-S) in relation to BS of 30%, but in contrast there was an increase in Zn TF (Fig. 4T). Sunflower plants grown at the highest BS had lower Cd BCF in their shoots (Fig. 4F) and Zn BCF in their shoots and roots (Figs. 4R-S) compared to plants grown at the lowest BS. Similarly, increasing BS resulted in lower TE BCF in tomato. There was lower Ba BCF in the roots (Fig. 4C) and lower Ni BCF in the fruit and shoot (Figs. 4M-N) of tomato plants grown at BS of 70%.

Cadmium can easily reach edible parts of the crops assayed compared to the other TEs (Figs. 4A-C, 4E-G, 4I-K, 4M-O, and 4Q-S). There was a strong restriction on Ba and Cu long distance-translocation from roots to edible parts of all crops (Figs. 4A-C and 4I-K), which was evidenced by the low Ba and Cu TFs (Figs. 4D and 4L). In general, lettuce, sunflower, and tomato presented a lower capacity for restricting Ba, Cd, Cu, Ni, and Zn concentration in their tissues than rice (Fig. 4).

There was no clear relationship between BCF and TF values (Fig. 4), which indicates that in addition to TE bioavailability, mechanisms involved in TE uptake and translocation affected TE concentration in the edible parts of the crops assayed. Sunflower and tomato plants had higher Cd and lower Zn translocation, respectively, compared with lettuce and rice (Figs. 4H and 4T). Tomato presented a high capacity for Ni translocation, as well as lettuce (Fig. 4P). In summary, our results suggest that increasing BS tends to decrease TE BCF, but this process strongly depends on physiological mechanisms of the crops involved in TE uptake and translocation.

**Discussion**

The ability to take up and accumulate TEs varies significantly depending on the plant species and genotype (Jolly et al. 2013; Gupta et al. 2019; Li et al. 2019). This ability is contingent on the TE bioavailability right from the very beginning and, subsequently, on the physiological mechanisms involved in TE uptake and translocation (Antoniadis et al. 2017). Consequently, agricultural practices that influence TE bioavailability (e.g., higher BS) often shape their accumulation in plants (Macedo et al. 2020).

There was no effect of BS on pseudo-total Ba, Cd, Cu, Ni, and Zn concentrations in the contaminated Entisol, with few exceptions (Fig. 1). This was a consequence of the effect of the higher pH and CEC resulting from the increasing BS, which often affects only the chemical distribution of the TEs in a soluble, readily exchangeable form, complexed with organic matter or hydrous oxides forms (Rieuwerts 2007). Thus, normally there is no effect of pH and CEC on the pseudo-total TE concentration. On the other hand, increasing BS reduces Ba, Cd, Cu, Ni, and Zn bioavailability in the Entisol (Pinto and Alleoni 2018), i.e., there was a reduction in TE fractions that can be absorbed and involved in the plant cell metabolism. Similar results have been pointed out in other studies, in which Ba, Cd, Cu, Ni, and Zn bioavailability and toxicity in different plant species decreased after increasing BS by liming (Guo et al. 2013; Han et al. 2013; Myrvang et al. 2016a; Cioccio et al. 2017).

When present in high concentrations in plant tissues, Ba, Cd, Cu, Ni, and Zn inhibit plant growth and decrease photosynthetic activity (Moya et al. 1993; Gupta et al. 2019; Lavres et al. 2019). In our study, the biomass production of lettuce exposed to Cu, Ni and Zn was considerably lower than the control (Figs. 2B-C), which also was the case with the leaf CO₂ assimilation and stomatal conductance of lettuce plants exposed to Ni and Zn, especially at BS of 30% (Table 2). Possibly, the lower biomass observed in lettuce exposed to Ni and Zn is related to an inhibitory effect of Ni and Zn on the activities of enzymes involved in photosynthetic carbon reduction cycles (Moya et al. 1993; Benzarti et al. 2008) and with changes in abscisic acid (ABA) synthesis that caused stomatal closure (Rucińska-Sobkowiak 2016).

Rauser and Dumbroff (1981) reported that bean (*Phaseolus vulgaris* L.) exposed to Ni and Zn presented increased ABA concentrations that led to stomatal closure, lower transpiration, and water stress. On the other hand, the Cu-induced suppression in biomass of lettuce (Figs. 2B-C), as well as in rice (Figs. 2D-F), was not related to chlorophyll concentration and leaf CO₂ assimilation (Table 2), suggesting that the Cu-induced toxicity in these plants was not directly related to these photosynthetic processes.
As a redox-active element, Cu can directly cause reactive oxygen species formation and induces lipid peroxidation of membranes and protein oxidation, leading to growth inhibition (Adrees et al. 2015), as reported for lettuce (Trujillo-Reyes et al. 2014) and rice (Du Costa et al. 2020). Cu toxicity decreased in lettuce only after increasing BS (Figs. 2B-C). This result is probably related to the fact that Cu bioavailability decreased more compared to Ni and Zn when BS was increased (Pinto and Alleoni 2018), resulting in lower Cu uptake compared to Ni and Zn (Figs. 3J-K, 3N-O, and 3R-S). As Cu is a redox-active element, the toxicity induced by this metal is very dependent on its concentration inside the plant tissues (Adrees et al. 2015).

Similar to lettuce, sunflower was more susceptible to toxicity induced by Ni and Zn compared with the other TEs, especially when the plants were grown at BS of 30% (Figs. 2G-I). However, differently from lettuce, Ni and Zn did not induce great changes in photosynthetic parameters measured in sunflower (Table 2). In addition to decreasing photosynthetic activity of plants, Ni and Zn can induce other metabolic disorders that compromise the biomass production, such as oxidative stress (Akladious and Mohamed 2017; Shahbaz et al. 2018) which often has been discussed as a primary effect of TEs exposure in plants (Clemens 2006). Shahbaz et al. (2018) assessed Ni-induced toxicity in sunflower grown in an Ni-polluted soil (77 mg Ni kg\(^{-1}\)) and reported that the oxidative Ni-induced stress significantly decreased plant biomass.

Shahbaz et al. (2018) observed that the use of biochar was essential to decreasing Ni bioavailability and increasing the biomass production of sunflower. In our study, increasing BS was essential to decreasing Ni bioavailability, allowing for the survival of sunflower grown on Ni-polluted Entisol (Figs. 2G-I). Similar results were reported by Macedo et al. (2020) in an Alfisol. Sunflower grown on Zn-polluted soil also had higher biomass at BS of 70% (Figs. 2G-I), probably due to a lower Zn concentration in its shoot and grains (Figs. 3Q-R). Excess Zn may inactivate enzymes that mitigate oxidative stress, such as superoxide dismutase (EC 1.15.1.1), catalase (EC 1.11.1.6), and ascorbate peroxidase (EC 1.11.1.11) (Akladious and Mohamed 2017).

It is probable that oxidative stress or water stress or both had been the main cause for the lower root biomass of tomato grown on Cd, Cu, Ni, or Zn-polluted Entisol at BS of 30% (Fig. 2L). Metals often reduce the elongation of the primary roots, impair secondary growth, increase root dieback or reduce root hair by inducing oxidative stress, which exert deleterious effects on root-absorbing area and water uptake (Rucińska-Sobkowiak 2016; Ahmad et al. 2018). Despite Cd, Cu, Ni and Zn reducing the root biomass of tomato, only Ni exposure reduced fruit production compared to control in tomato plants grown at BS of 30% (Fig. 2J). Probably, this result is related to the high Ni concentration observed in the tomato fruit compared to the other TE concentrations (Figs. 3A, 3E, 3I, 3M, and 3Q).

The difference between levels of sufficiency and toxicity of Ni for plants is very little, because this TE is required in low concentrations (Macedo et al. 2016, 2020). High Ni concentrations in tomato can be a problem not only for plants but also to human health (Correia et al. 2018). Nickel concentration recorded in the edible parts of the crops grown in the Ni-polluted Entisol in our study were above the maximum permitted level (EPA-IRIS 1987b), which means that the intake of these crops by humans could lead to health problems (Petrosino et al. 2018).

As for Ni, the concentrations of Ba and Cd in the edible parts of the crops assayed exceeded the maximum levels permitted by EPA-IRIS (1987a), and FAO and WHO (2011), respectively, when the plants were grown in the Entisol spiked with TE concentrations corresponding to the prevention levels proposed by CETESB (2014). Harmful changes to soil and groundwater quality can occur in soils presenting TE concentrations corresponding to the prevention levels but direct and indirect potential risks to human health are expected only in soils presenting TE concentrations equal to or above the intervention levels for agricultural areas (CETES-ESB 2014). Therefore, the prevention levels established by CETESB (2014) for Ba, Cd, and Ni should perhaps be revised for soils presenting low OC and clay contents and low CEC, such as Entisols (Rieuwerts 2007), because Ba, Cd, and Ni concentrations recorded in the edible parts of the crops assayed in our study (Figs. 3A-B, 3E-F and 3M-N) were potentially dangerous to human health (Tchounwou et al. 2012; Petrosino et al. 2018), regardless of BS.

Entisols present low amounts of negative charges (low CEC) compared with other soils because of their low organic carbon and clay contents (Rieuwerts 2007). Given this fact, increasing the amount of variable negative charges through liming (Raij et al. 1996) to eventually bind the metals—a considerable part of these metals remains accessible for plant uptake in the soil solution. Entisol has a lower capacity for controlling TE bioavailability than clayey soils with higher OC content and CEC, which favor TE accumulation (Melo et al. 2014). This becomes clearer if we consider that we spiked the Entisol with TE in the order Ba > Zn > Cu > Ni > Cd (according to their concentration), and the crops assayed accumulated TEs in the following order: lettuce, Ba = Zn > Cu = Ni > Cd; rice, Zn > Ba > Ni > Cu > Cd; sunflower, Ba > Zn > Cu > Ni > Cd; and tomato, Ba = Zn > Ni > Cu > Cd (Figs. 3D, 3H, 3L, 3P, and 3T). It is possible that, on account of its particular characteristics, increasing BS in Entisol was not sufficiently effective in reducing Ba, Cd, Cu, Ni, and Zn accumulation in lettuce, rice, sunflower and tomato (Figs. 3 and 4) compared with other soils (Han et al. 2013; Cioccio et al. 2017; Li et al. 2019; Macedo et al. 2020).
The effect of increasing BS on TE accumulation varied depending on the metals and plants (Figs. 3 and 4) because T accumulation in the edible parts of the crops do not depend on their bioavailability only, but also on mechanisms involved on TE uptake and translocation of each plant species (Antoniadis et al. 2017). For example, lettuce grown at BS of 30% exceeded the maximum levels for Cu and Zn proposed by the FAO and WHO (2011) (Figs. 3J and 3R), which rice and tomato did not. Sunflower also exceeded the maximum level for Zn proposed by the FAO and WHO (2011) (Fig. 3Q).

As reported in other studies (Singh et al. 2010; Pereira et al. 2011; Melo et al. 2014; Gupta et al. 2019), Ba, Cd, Cu, Ni, and Zn tissue concentrations and BCFs for lettuce, rice, sunflower, and tomato tissues followed the order: roots > shoot > grains or fruits (Figs. 3 and 4). Roots are normally the first structure of the plant in contact with TEs, and they present mechanisms to avoid excessive metal translocation, with the exception of hyperaccumulators (Antoniadis et al. 2017; Gupta et al. 2019).

Meng et al. (2019) reported that Cd had accumulated more in the roots than shoot in leafy vegetables due to the higher synthesis of phytochelatins [PCs, (γ-Glu-Cys)n-Gly, with n = 2–11] in the roots. Phytochelatins act on Cd\(^{2+}\) chelation and its transport from the cytosol to the vacuole (Clemens 2006). Kendziorek et al. (2016) suggested that Cd and Zn distribution among roots and shoot was related to expression of the gene HMA4 (involved on metals efflux) in tomato roots. TE translocation from roots to shoot mainly depends on the rate of trapping in compartments of root cells, the mobility within the root symplast and across barriers, such as endodermis, loading into the xylem, and upward mobility in the xylem (Clemens and Ma 2016). Therefore, physiological mechanisms control TE translocation from roots to shoot, although there is still a great influence of highest TE bioavailability on their shoot accumulation as a result of the higher TE uptake in this scenario. For instance, Melo et al. (2014) mentioned that there was a positive correlation of Ba and Cd bioavailability with Ba BCF\(_{\text{roots}}\), Ba BCF\(_{\text{shoot}}\), Cd BCF\(_{\text{roots}}\), and Cd BCF\(_{\text{shoot}}\) in different crops, but there was no correlation of TE bioavailability with Ba TF and Cd TF.

Increasing BS (lower TEs bioavailability) decreased the Cd BCF\(_{\text{shoot}}\) in lettuce and sunflower, Ni BCF\(_{\text{shoot}}\) in lettuce and tomato, and Zn BCF\(_{\text{shoot}}\) in rice and sunflower grown in a polluted Entisol. Interestingly, there was no effect of BS on Ba and Cu BCF\(_{\text{shoot}}\) nor Ba and Cu BCF\(_{\text{grains or fruits}}\) in the crops assayed in our study (Figs. 4A-C, 4E-G, 4I-K, 4M-O, and 4Q-S). Myrvang et al. (2016b) evaluated the effect of liming on Ba transfer from soil to shoot of different crops and observed that there was a considerable variation in Ba BCF\(_{\text{shoot}}\), regardless of Ba bioavailability, which was attributed to physiological differences between the plant species.

Trace element accumulation in leaves (or shoot) depends on physiological factors, such as the TE loading from xylem and availability of metal-binding molecules (Clemens and Ma 2016), as observed in rice exposed to Cu (Ando et al. 2013). Furthermore, after entering into the shoots, some TEs such as Cu can be accumulated in the epidermis, which serves as an effective mechanism for their detoxification by decreasing metal influx into mesophyll (Seregin and Kozhevnikova 2020; van der Ent et al. 2020). These processes restrict TE redistribution to grains and fruits (Seregin and Kozhevnikova 2020), and probably occurred in our study for Ba and Cu, because there was a strong restriction on Ba and Cu translocation from roots to edible parts of all crops compared to the other TEs (Fig. 4). Nevertheless, Hladun et al. (2015) stated that Cu presented high mobility inside radish (Raphanus sativus L.). This finding reinforces the belief that there is significant variation between plant species and genotypes in terms of their ability to take up and accumulate TEs (Jolly et al. 2013; Gupta et al. 2019; Li et al. 2019).

Cadmium easily reached edible parts of the crops assayed compared to the other TEs, which is different from the results observed for Ba and Cu (Figs. 4A-C, 4E-G, 4I-K, 4M-O, and 4Q-S). Hladun et al. (2015) also mentioned that Cd presented high mobility inside radish. Meanwhile, Riesen and Feller (2005) described that Ni and Zn had higher mobility inside wheat (Triticum aestivum L.) than Cd and suggested that this result is associated with the plant’s capacity to transfer metals from xylem to phloem. However, this transfer process is unknown for the majority of TEs and crops, except for some TEs in rice (Clemens and Ma 2016; Seregin and Kozhevnikova 2020).

In our study, in general, lettuce, sunflower and tomato had a lower capacity for restricting Ba, Cd, Cu, Ni, and Zn uptake and translocation than rice, even rice grown in Entisol at a lower BS (50% vs. 70%; Figs. 4A-C, 4E-G, 4I-K, 4M-O, and 4Q-S). Probably this result is related to efficient controlling of TE distribution to shoot from the nodes of rice, which is a hub for metal distribution in graminaceous crops (Yamaji and Ma 2014). The distribution of TEs among leaves and grains in rice depends on phloem loading, the efficiency of xylem-to-phloem transfer, the rates of various symplast-to-apoplast and apoplast-to-symplast transport processes, and the availability of storage sites (Clemens and Ma 2016).

Several types of metal-binding compounds, including nicotianamine and PCs, were reported to be relevant for TE transport in the phloem of crops destined for human consumption (Gupta et al. 2019). These compounds can affect TE translocation to grains or fruit from the roots (Gupta et al., 2019). However, although studies have been performed evaluating TE accumulation in plants, most processes involved in TE translocation are still poorly known or
unknown for most of the plant species consumed by humans (Seregin and Kozhevnikova 2020).

**Conclusions**

In general, increasing BS did not attenuate photosynthetic changes induced by Ba, Cd, Cu, Ni, and Zn in the crops cultivated in the Entisol, because this agricultural practice was not so effective in reducing the TE bioaccumulation.

The photosynthetic changes observed in the crops assayed varied depending on the metal and plant species. There was no strong correlation between the photosynthetic parameters measured and biomass production, which suggests that the suppression of biomass induced by Ba, Cd, Cu, Ni, or Zn is related to other metabolic disorders in addition to the impairment of CO₂ assimilation or chlorophyll synthesis in the crops assayed, with the exception of Ni and Zn in lettuce.

Increasing BS was not consistent in decreasing Ba, Cd, Cu, Ni, and Zn accumulation in the edible parts of lettuce, rice, sunflower, and tomato grown in the Entisol, which was probably related to the low capacity of this soil for controlling TE bioavailability due to its low organic carbon and clay contents and low cation exchange capacity.

Barium, Cd, Cu, Ni, and Zn bioaccumulation in the edible parts of the crops was affected by TE bioavailability, which means that other agricultural practices could perhaps be more efficient than increasing BS to avoid the bioaccumulation of TEs into the edible parts of crops grown in Entisol.

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**Declarations**

**Conflict of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

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