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Physiological, biochemical and nutritional changes in soybean in response to application of steel slag

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Abstract

Steel slag is a powdery industrial residue that has CaO, MgO and SiO_2 in its composition, which enables its use in agriculture for soil acidity correction. Most studies involving this residue have focused on understanding its effects on the soil, not always considering its action on the plant metabolism. Thus, the present study aimed to evaluate physiological, biochemical and nutritional changes in soybean plants due to application of lime and steel slag on the soil surface or by incorporation. The experiment was carried out in the field, with six soil acidity corrective materials: stainless steel slag, steel slag, ladle slag, wollastonite slag, dolomitic lime and calcined dolomite, plus a negative control, which did not receive correctives. Two application methods were adopted: soil surface application or incorporation. Sixty days after application, the soybean crop was established. Soybean response changed with the application method, since incorporation of corrective materials provided greater production of fresh and dry leaf mass and stem fresh mass, increased chlorophyll b and leaf K levels, and contributed to a greater number of plants per hectare and pods per plant, compared to surface application. Besides such benefits, there was no difference between the effect of application methods on soybean yield, indicating that both incorporation and surface application are efficient in increasing soybean grain yield. The correctives steel slag, wollastonite and calcined dolomite provided significant increases in soybean yield.

Keywords: Soil acidity, Liming, Slags, Silicate, *Glycine max.*
Abbreviations: CEC_ Cation Exchange Capacity; ROS_ Reactive Oxygen Species; Fe_ Iron; Mn_ Manganese; Al_ Aluminum; DSW_ Dry Stem Weight; SS_ Steel Slag; W_ Wollastonite; C_Control; LS_ Ladle Slag; SSS_ Stainless Steel Slag; CDL_ Calcined Dolomitic Lime and DL_ Dolomitic Lime; S_ Superficial Application; I_ Incorporation; BS_ Base Saturation. K_ Potassium; N_ Nitrogen; P_ Phosphorus; Ca_ Calcium; Mg_ Magnesium; S_ Sulfur; TSP_ Total Soluble Proteins; POD_ Peroxidase; CAT_ Catalase; SOD_ Superoxide Dismutase; SRA_ Antioxidative System; LA_ Leaf Area; FLW_ Fresh Leaf Weight; DLW_ Dry Leaf Weight; FSW_ Fresh Stem Weight; DSW_ Dry Stem Weight; Si_ Silicon.

Introduction

Soybean (*Glycine max*) is the crop of highest productive expression in Brazil. In the 2019 harvest, the area and volume of soybean production corresponded to approximately 48% of the 240.65 million tons of grains produced in the country (Conab, 2019). Most soybean cultivation involves no-till system (Pauletti et al, 2014) and liming (Lopes et al, 1991)

Brazilian soils have several limiting attributes for the crop yield, including acidity, toxic elements (Al and Mn), and low cation exchange capacity (CEC) (Gama et al., 2007). Liming is frequently used to neutralize the soil acidity, reduce the acidity effect on plant development, improve the microorganism activity, reduce the abiotic stress, and increase the nutrient availability (Martins et al, 2017). Lime is the most used corrective material; however, residues from the metallurgical industries such as steel slags can also be successfully employed in agricultural activity (Deus et al., 2019).

Steel slags are Ca and Mg silicates containing CaO, MgO, SiO_2, P_2O_5, FeO and MnO in their composition. Their chemical and physical constitution may vary due to the different processes and different raw materials used in metallurgical industries (Deus et al., 2019). Steel slags can be adopted to correct soil acidity; increase pH levels, exchangeable calcium, exchangeable magnesium, CEC, and soil base saturation; improve phosphorus and silicon availability, and reduce Fe, Mn and Al toxicity (Pulz et al., 2008). It must also be emphasized that the use of steel slag in agriculture is a viable alternative for the final disposal of this material since its waste is inappropriately discarded in landfills and improper places.

Some studies have shown that steel slags efficiently replace lime in soil acidity correction since they dissolve and make elements available to the plants more rapidly and at greater depths (Corrêa et al., 2009; DEUS et al., 2019).

Another advantage of slag application is Si supply to the crop. Silicon has been evidenced to have an indirect effect on the productivity of soybean crops by improving the plant architecture and the leaf arrangement, which makes the plants stronger and more resistant to lodging (Agarie et al., 1998).

Plants may alter their metabolism when exposed to inadequate environmental conditions and abiotic stress. Excess elements in the soil, such as manganese, may induce abnormal metabolic events that can lead to the production of reactive oxygen species (ROS) (Amaro et al., 2018). Unless ROSs are neutralized, they may affect the cell structure and cause cellular death. Oxidative damage to the plant cell structures creates an imbalance between antioxidant activity and ROS production, which activates enzymes like superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT) (Qi et al, 2018).

Therefore, better understanding how different types of slag can be used to correct the soil acidity and improve the plant development is important. Steel slag is suggested to alter the capacity of plants to respond to metabolic changes caused by biotic and abiotic factors. Thus, the aim of the present study was to evaluate physiological, biochemical and nutritional changes in soybean plants due to surface application or incorporation of lime and steel slags.

Results

Soybean physiological and nutritional characteristics

The application method influenced Fresh Leaf Weight (FLW), Fresh Stem Weight (FSW), Electrolyte Loss (EL) and Chlorophyll b (Table 1). Incorporation of acidity correctives led to greater FSW and FLW than surface application. Similarly, the highest EL and chlorophyll *b* levels were found when the correctives were incorporated into the soil.

The tested corrective materials had an effect on Dry Leaf Weight (DLW) and Chlorophyll b (Table 1). Stainless steel slag significantly influenced DLW, compared to control, while the remaining treatments had no significant differences. The lowest Dry Stem Weight (DSW) was obtained with the control treatment. Chlorophyll *b* levels ranged from 16.0 µg cm^{-2} for the control to 23.8 µg cm^{-2} for wollastonite; however, there was no significant difference between the studied correctives.

The nutrients K and B were also influenced by the application method, since K level was higher with the incorporation of correctives while B level was higher with surface application. Considering the soil acidity correctives, there was also a significant effect on the leaf levels of Ca, Mg, Fe, Mn, and Zn (Supplementary Table 3).

Higher levels of the nutrient Ca were provided by the correctives SS, W and SSS, which were similar to each other, whereas limestones did not differ from control (Supplementary Table 3). Mg levels obtained with DL were higher than those found with SS and W and similar to those resulting from control, LS, SSS and CDL application.

Fe level obtained with the control treatment was superior to that found with LS and W and similar to the levels resulting from SS, SSS, CDL and DL, while for Mn levels, the control was superior to all other treatments. Regarding Zn levels, control treatment was superior to SSS and DL and similar to SS, W, LS and CDL (Supplementary Table 3).

Biochemical characteristics and soybean productivity

The analyzed biochemical parameters indicated interactions between the application method and the acidity correctives considering the enzyme SOD, which is part of the plant's antioxidative response system (Tables 2 and 3). When incorporation was adopted, SOD activity was the same, regardless of the corrective material. However, for surface application, W and the control were similar to each other in showing higher SOD activity, compared to the other correctives.

Considering the factors separately, there was a difference between the application methods since incorporation resulted in higher number of plants per hectare and higher number of pods per plant, compared to surface application.

The biochemical parameter Total Soluble Proteins (TSP) was influenced by the corrective materials, ranging from 17.7200 mg g^{-1} for the control to 25.9400 mg g^{-1} for steel slag, which showed no difference from the other treatments (Table 2).

Discussion

Application of correctives by incorporation resulted in the highest values of the parameters FLW, FSW, EL, Chlorophyll b, K level, number of plants, and number of pods/plants, compared to surface application. This was possibly due to the improved distribution of correctives (0-0.20 m) provided by incorporation, also favoring soil aeration and, consequently, improving the development of the plant's root system with higher nutrient and water absorption.

Wollastonite application had the greatest effect on Chlorophyll *b*, while the remaining treatments showed no significant differences (Supplementary Table 3). Chlorophyll *b* is characterized as an accessory pigment, responsible for aiding in light absorption (Silva et al., 2014), maximizing energy absorption that effectively acts in the photochemical reactions (Gill & Tuteja, 2010) and in the photosynthesis maintenance (Imtiaz et al., 2016).

An increased leaf Ca level provided by the treatment with Wollastonite was due to the Ca percentage present in this corrective material.

Mg concentration in soybean leaves was higher with DL, compared the other treatments. This increase is related to the composition of such material, which has higher MgO values than the other correctives (Supplementary Table 2), combined with the rain that occurred during the experimental period, leading to good nutrient distribution.

The leaf levels of the nutrients Ca, Mg, N and P remained within the adequate range for soybean, except K, which kept below the optimal range, according to Ambrosano et al. (1997).

The higher leaf level of B provided by the surface application of acidity correctives can be explained by the storage of part of the available form of this element in the superficial layer of the soil, together with organic matter (Raij et al. 1997). Leaf Fe level was higher with the control than with the other treatments.

The increased Mn level in soybean leaves was not within the adequate range proposed by Ambrosano for the crop: from 20 to 100 mg kg^{-1}. In this study, Mn values were higher than 100 mg kg^{-1} for all treatments. According to Rosolem et al. (1992), the range from 140 mg kg^{-1} to 300 mg kg^{-1} Mn in mature leaves corresponds to toxic levels for soybean crops. The highest Mn levels (300 mg kg^{-1}) obtained with the control treatment might have contributed to the lower

Table 1. Leaf area (LA), leaf fresh mass (FLW), leaf dry mass (DLW), stem fresh mass (FSW), stem dry mass (DSW), leaf silicon content (Si), relative water content in leaf tissue (RWC), loss of electrolytes (EL) and pigment content: chlorophyll *a* (Clo *a*), chlorophyll *b* (Clo *b*) and carotenoids (Car) as a function of the effect of the application mode and correctives of soil acidity on soybean cultivar TMG 7062 IPRO.

Treatments	LA	FLW	DLW	FSW	DSW	Leaf silicon content (Si)	RWC	EL	Clo *a*	Clo *b*	Car
Application (A)	cm² plant^{-1}	------------	g plant $^{-1}$	------------		mg kg^{-1}	%		µg cm^{-2} of leaf		
Incorporated	4924.9 a	54.0 a	24.3 a	149.7 a	43.35 a	3.05 a	84.8 a	6.3 a	35. 0 a	22.3 a	8.7 a
Superficial	3509.1 a	39.7 b	19.3 a	96.2 b	43.92 a	2.89 a	88.3 a	5.2 b	34.0 a	19.2 b	8.5 a
F	47.82^{ns}	11.59*	3.73^{ns}	20.71*	6.37^{ns}	0.22^{ns}	3.19^{ns}	1.29*	1.16^{ns}	20.71*	6.37^{ns}
Correctives (C)											
SS	4117.4 a	43.8 a	21.9 ab	126.8 a	43.00 ab	2.37 a	88.8 a	6.2 a	35.0 a	20.8 a	8.6 a
W	4244.7 a	46.0 a	22.1 ab	120.5 a	44.50 ab	3.18 a	87.3 a	4.5 a	36.7 a	23.8 a	8.8 a
C	3109.7 a	35.7 a	17.5 b	88.7 a	49.00 a	3.35 a	89.3 a	5.7 a	30.8 a	16.0 b	8.0 a
LS	4537.5 a	47.6 a	22.5 ab	136.1 a	43.00 ab	2.62 a	83.9 a	6.7 a	35.0 a	21.6 a	8.3 a
SSS	5274.4 a	58.2 a	25.6 a	150.1 a	40.62 b	2.75 a	84.2 a	4.8 a	36.9 a	21.9 a	9.1 a
CDL	4313.3 a	47.3 a	21.9 ab	124.0 a	45.12 ab	2.78 a	82.8 a	5.3 a	35.1 a	21.4 a	9.1 a
DL	3922.0 a	49.1 a	21.1 ab	114.7 a	40.25 b	2.73 a	88.4 a	7.2 a	34.2 a	20.1 ab	8.2 a
F	0.28^{ns}	1.24^{ns}	2.12*	1.41^{ns}	2.52*	2.00^{ns}	0.69^{ns}	0.79^{ns}	1.19^{ns}	5.84*	0.74 ^{ns}
A x C	2.02^{ns}	1.72^{ns}	1.82^{ns}	1.97^{ns}	2.07^{ns}	1.92^{ns}	0.39^{ns}	0.81^{ns}	0.65^{ns}	0.48^{ns}	0.64^{ns}
VC (%) plot	55	33	43	35	46	42	8	61	3	10	4
VC (%) subplot	29	36	21	36	22	21	11	54	15	13	16

Averages followed by different letters in the columns differ among themselves. By the Tukey test at 5% (*) and 1% (**) probability. SS – Steel slag. W – Wollastonite. C – control. LS – Ladle slag. SSS – Stainless steel slag. CDL – Calcined dolomitic lime. DL – Dolomitic lime. ns - not significant.

Table 2. Total soluble protein content (PTS), activity of the enzymes Superoxide dismutase (SOD), Peroxidase (POD), Catalase (CAT), N°. of plants per hectare, N°. of pod / plant, N°. of grains / plant and productivity depending on the application and the corrective effect of soil acidity on soybean cultivar TMG 7062 IPRO.

Treatments	TSP	SOD	POD	CAT	Number of plants per hectare	Number of pods/plant	Number of grains/plant	Silicon content in the grain	Yield (t ha $^{-1}$)
	(mg g^{-1})	(UI µg proteín^{-1})	µKat µg proteín-1					mg kg^{-1}	
Application (A)									
Incorporated	24.3 a	0.98 a	2.7 a	370.4 a	550594 a	78 a	2.0 a	1.05 a	6.46 a
Superficial	20.8 a	1.03 a	2.8 a	362.5 a	444346 b	53 b	2.0 a	1.04 a	5.30 a
F	37.42^{ns}	1.01^{ns}	0,57^{ns}	0,05^{ns}	46,15**	17,81*	1,00^{ns}	0,79^{ns}	3,88^{ns}
Correctives (C)									
SS	25.9 a	0.86 b	2.7 a	291.9 a	463194 a	75 a	2.0 a	1.09 a	7.18 a
W	22.2 ab	1.10 ab	2.7 a	426.9 a	515277 a	53 c	2.0 a	1.21 a	6.25 ab
C	17.7 b	1.16 a	2.8 a	345.7 a	519443 a	55 bc	2.0 a	1.01 a	4.32 c
LS	23.8 ab	0.94 ab	2.8 a	389.4 a	513548 a	64 abc	2.0 a	0.86 a	5.98 abc
SSS	21.6 ab	1.02 ab	2.7 a	419.8 a	503471 a	75 a	2.0 a	1.16 a	5.22 bc
CDL	22.4 ab	1.09 ab	2.8 a	383.5 a	474999 a	68 ab	2.0 a	1.03 a	6.40 ab
DL	24.2 ab	0.87 ab	2.8 a	307.9 a	492360 a	65 abc	2.0 a	0.94 a	5.80 abc
F	2.49*	3.08*	1.62^{ns}	1.67^{ns}	0.43^{ns}	2.87*	0.64^{ns}	0.64^{n}	4.86**
A x C	0.66^{ns}	2.76*	0.80^{ns}	1.91^{ns}	0.43^{ns}	1.88^{ns}	1.53^{ns}	0.33^{ns}	1.00^{ns}
VC (%) plot	21	18	6	34	12	34	7	26	37
VC (%) subplot	20	19	4	31	19	23	15	29	20

Averages followed by different letters in the columns differ among themselves. By the Tukey test at 5% (*) and 1% (**) probability. SS – Steel slag. W – Wollastonite. C – control. LS – Ladle slag. SSS – Stainless steel slag. CDL – Calcined dolomitic lime. DL – Dolomitic lime. ns - not significant.

Table 3. Deployment of the interaction x corrective for the enzyme Superoxide dismutase (SOD) (UI µg proteín^{-1}).

Correctives	Forms of application	
	Incorporated	Superficial
SS	0.90 aA	0.81 aC
W	0.97 aA	1.24 aB
C	0.99 bA	1.33 aA
LS	0.98 aA	0.91 aC
SSS	0.90 aA	1.13 aC
CDL	1.23 aA	0.95 aC
DL	0.89 aA	0.85 aC

SS – Steel slag. W – Wollastonite. C – control. LS – Ladle slag. SSS – Stainless steel slag. CDL – Calcined dolomitic lime. DL – Dolomitic lime. ns - not significant. Capital letters correspond to the comparisons between the soil acidity correctives within the same mode of application. Lower case letters correspond to comparisons between the mode of application for the same soil acidity correction by the Tukey test at a level of 5% (*) and 1% (**) probability.

number of pods per plant in the control (Supplementary Table 3), compared to the other treatments, corroborating the study by Heenan & Campbel (1980).

TSP content is regarded as a reference indicator to determine and quantify several other enzyme activities. SS, either incorporated or applied on the soil surface, was the only treatment that had an effect on soluble proteins, probably because it provided greater protease activity, which decreased manganese toxicity for SOD in soybean leaves.

Plants are capable of developing biochemical responses to survive stress; such responses are generated by an antioxidative system (SRA) and have been evaluated as stress indicators (Souza et al, 2020). In the present study, there was an increase in the activity of the enzyme SOD in response to the surface application of acidity correctives. The greater SOD activity obtained with the control treatment can be related to the excessive leaf level of manganese present in the treatment, compared to the incorporated correctives, which showed low SOD activity. Thus, activity of other enzymes (CAT and POD) was not observed, i.e., only the enzyme that is considered the first line of the plant defense against stress was activated: SOD. However, this evidences that the plant has adapted to the environment and has not activated the other enzymes (CAT and POD) through its defense mechanism.

Critical Mn^{+2} levels in the leaves (below or above the adequate range) cause oxidative stress due to an increase in the concentration of hydrogen peroxide and malondialdehyde, an indicator of lipid peroxidation (Amaro et al., 2018). Such oxidative stress was evidenced by the enzyme SOD in soybean leaves. In addition, in the present study, even though Mn^{+2} was above the optimal level for soybean leaves, it did not inhibit the availability of Ca^{+2}, Mg^{+2} and Fe^{+2} in the leaves. The number of plants per linear meter increased with the incorporation of soil acidity correctives in a no-till system (Rheinheimer et al, 2000). The number of pods per plant varied from 53 for incorporation to 78 for surface application (Supplementary Table 3). This might have occurred because larger soybean plant populations are capable of producing more pods due to the greater number of ramifications, which determines higher knot production potential and, consequently, higher number of pods per plant (Mauad et al., 2010). Thus, this positively influenced the number of pods per plant considering the two analyzed factors.

There were satisfactory differences in productivity (t ha^{-1}) with the application of the soil acidity correctives; steel slag led to the highest productivity, showing an average value of 7.18 t ha^{-1}, while control had an average value of 4.32 t ha^{-1}. Thus, the increased productivity observed in the present study is due to the residual effect of using steel slags as soil acidity corrective over time in the same area, which acted as a nutrient supplier to the soil and had a positive effect on productivity. It must be highlighted that productivity is also favored by other factors like genotypes of high productive potential and some environmental factors (Prado et al., 2001).

Material and Methods

Description of the experimental site and soil

The experiment was conducted between July 2019 and February 2020, under field conditions, at the College of Agronomic Sciences – São Paulo State University (Unesp), Botucatu, São Paulo State, Brazil (22°50′19″ S and 48°25′54″ W, at 738m above sea level). The soil in that area was classified as Rhodic Hapludox (Soil Survey Staff, 2014), a dystrophic Red Latosol, according to the classification of Embrapa (2018).

The experiment was established in 2010 with the surface application and incorporation of the soil acidity corrective materials described on item 1.4. Still in 2010, before application of the corrective materials, the plots designated to receive treatments by incorporation were prepared by plowing with a reversible disc plough and harrowing with leveling disc harrow. Then, the corrective materials were manually applied on the soil surface and mechanically incorporated to 0–20 m. After application, the no-tillage system was followed (Deus et al., 2020) for all treatments until 2013.

The liming was reapplied in 2013 and 2017, considering the soil chemical analysis for those years and the chemical characteristics of each corrective material; the dose was calculated to increase base saturation to 70%. The corrective materials were applied on the soil surface and incorporated to 0-20 cm depth, following the proposed treatments. After each reapplication, the crops were conducted in a no-tillage system for all treatments.

In July 2019, chemical analysis was performed to characterize the soil at the 0-20cm layer, following the methodology proposed by Raij et al. (2001).

Monthly rainfall and maximum, medium and minimum temperature are shown in Supplementary Fig 1.

Treatments, experimental design and study development

Treatments consisted of two application methods (surface application and incorporation) of six soil acidity corrective materials, namely, steel slag (SS), ladle slag (LS), stainless-steel slag (SSS), Wollastonite (W), Dolomitic lime (DL) and calcined dolomitic lime (CDL), in addition to one control treatment (C), to which no corrective material was applied.

Experimental design was in randomized blocks with $42m^2$ (6m×7m) subplots and four replicates. The major plots were compared for the application method, surface application or incorporation, while the sub-plots were compared for the applied corrective materials.

The plots that received treatments by incorporation were prepared with a grid of disc levelers; then, in October 2019, the correctives were manually applied on the soil surface and mechanically incorporated to 0–20 m with an intermediate degree grid. For the plots receiving surface treatments, the corrective materials were manually applied on the soil surface.

The used dose of each corrective was calculated to increase base saturation to 70%, considering the result of the soil chemical analysis (Supplementary Table 1) and the chemical composition of each corrective (Supplementary Table 2). The chemical and physical characterization of corrective materials was carried out according to the Brazilian Legislation for Limestone (Alcarde, 2009).

After 60 days of application of the acidity correctives, soybeans of the cultivar 'TMG 7062 IPRO' were sown. The seeds were previously treated with the fungicide carboxin (carboxanilide) + thiram (dimethyldithiocarbamate) (9.6 g a.i. per 40 kg seeds) and the insecticide thiamethoxam (34 g a.i. per 40 kg seeds) and inoculated with liquid inoculum (5 x 10^9 CFU *Bradyrhizobium japonicum* mL^{-1}).

Sowing was performed in November 2019, adopting 0.45 cm row spacing and 20 seeds m^{-1} sowing rate. Fertilization was conducted based on the recommendations for soybean by Raij et al. (1996) and on the chemical characteristics obtained in the soil analysis (Supplementary Table 1), considering the average of all treatments, except the control treatment. Thus, 300 kg ha^{-1} of the formula 02-20-20 (N-P_2O_5-K_2O) were applied.

Plant measurements

During full blooming (70 days after germination), analyses included leaf area (cm^2) measurement with a leaf area meter model LICOR LI-3000; fresh and dry masses of leaves and stems; relative water content (RWC) (Barr et al. 1962); electrolyte loss (EL) (Lafuente et al., 1991); pigment content (Hiscox & Israelstam, 1979); leaf levels of macro and micronutrients (Malavolta et al., 1997), Total Soluble Proteins (TSP) (Bradford, 1976) and silicon, and activity of the enzymes SOD (Giannopolitis and Ries, 1977), POD and CAT (Lock, 1963). For both variables, 2 to 5 leaves were collected from the middle third of the plant to perform all analyses.

At the end of the crop cycle, evaluations included number of pods per plant, number of grains per pod, silicon content in the grain, mass of 100 grains, and yield. Soybean harvest was manually performed 115 days after seedling emergence and consisted of collecting 2 lines of 2 meters per subplot; then, humidity was corrected to 13% and the yield was calculated as t^{-1} ha.

Statistical analysis

Data were subjected to Shapiro-Wilk test for normality. Results underwent analysis of variance and, when significant, were compared according to Tukey's test at 5% probability. Statistical analysis was performed with the statistical software AgroEstat (Barbosa; Maldonado, 2015).

Conclusions

Application of correctives by incorporation favored soil aeration, which increased leaf biomass, stem weight, number of plants per linear meter, pigment content and, consequently, number of pods per plant.

The levels of micronutrients (B, Cu, Fe and Zn) were within the adequate range for the crop, except manganese, which was toxic, triggering SOD activity (stress indicator) and promoting, especially for the control treatment, a decrease in the number of pods per plant and consequently lower soybean productivity.

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Declaration of Competing Interest

The authors have no conflicts of interest to declare.

References

Agarie S, Hanaoka N, Ueno O, Miyazaki A, Kubota F, Agata W, Kaufman PB (1998) Effects of silicon on tolerance to water deficit and heat stress inrice plants (Oryza sativa L.), monitored by electrolyte leakage. Plant Prod Science. 1:96-103.

Amaro ACE, Baron D, Ono EO, Rodrigues JD (2020) Physiological effects of strobilurin and carboxamides on plants: an overview. Acta Physiologiae Plantarum. 42:4.

Alcarde JC (2009) Official Methodology for Acidity Corrective Analysis. Porto Alegre-RS, 58p.

Ambrosano EJ, Tanaka RT, Mascarenhas HAA, Raij B van, Quaggio JÁ, Cantarella H (1997) Leguminosas e oleaginosas. In: RAIJ, B. van; Cantarela, H.; Quaggio, J. A.; Furlani, A. M. C. (Eds.). Recomendações de adubação e calagem para o Estado de São Paulo. 2 ed. Campinas: Instituto Agronômico. 2:187-202 (Boletim Técnico 100).

Barbosa JC, Maldonado Junior W (2015) AgroEstat – Sistema para Análises Estatísticas de Ensaios Agronômicos. Jaboticabal: UNESP.

Barr HD and Weatherley PE (1962) A re-examination of the relative turgidity technique for estimating water deficit in leaves. Aust J Biol Sci. 413-428.

Bradford MM (1976) A rapid and sensitive method for the microgram quantities of protein utilizing the principle of protein-dye-binding. Anal Biochem. 72:248–254.

Companhia Nacional de Abastecimento (2019). Sexto levantamento de avaliação da safra 2019/2020. Brasília, p. 1-31.

Corrêa JC, Büll LT, Crusciol CAC, Morais MH (2009b) Alteração de atributos físicos em latossolo com aplicação superficial de escória de aciaria, lama cal, lodos de esgoto e calcário. Revista Brasileira de Ciência do Solo. 33: 263-272.

Deus ACF, Bertani RMA, Meirelles GC, Soares AAVL, Moreira LLQ, Büll LT, Fernandes DM (2019) The Comprehensive Utilization of Steel Slag in Agricultural Soils. In: Recovery and Utilization of Metallurgical Solid Waste. 10p.

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (2018) Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. Embrapa, E-book, Brasília

Gama JRFN, Carvalho EJM, Rodrigues TE, Valente MA (2007) Solos do estado do Pará. In: Cra Vom MS, Viégas IJM, Brasil EC (Ed.). Recomendações de adubação e calagem para o estado do Pará. Belém: Embrapa Amazônia Oriental, 19-29.

Gill SS, Tuteja N (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiology and Biochemistry. 48:909-930.

Giannopolitis CN, Ries SK (1977) Superóxido dismutases. I. Occurrence in higher plants. Plant Physiology 59:309–314.

Heenan DP, Campbel OG (1980) Growth, yield componets and seed composition of two soy-bean cultivars affected by manganese supply. Aust J Agric Res. 31: 471 – 476.

HiscoX JD, Israelstam GF (1979) A method for the extraction of chlorophyll from leaf tissue without maceration. Canadian J Botany.57:1132-1334.

Imtiaz M, Rizwan MS, Mushtaq MA, Ashraf M, Shahzad, SM, Yousaf B, Saeed DA, Rizwan M, Nawaz A, Mehmood S, Tu S (2016) Silicon occurrence, uptake, transport and mechanisms of heavy metals, minerals and salinity enhanced tolerance in plants with future prospects: A review. Journal of Environmental Management. v.183, 3:521- 529.

Korndörfer GH, Pereira HS, Nolla A (2004) Análise de silício no solo, planta e fertilizante. Uberlândia: GPSi 50p. (Boletim Técnico n° 02).

Lafuente MT, Belver A, Guye MG, Salveit ME (1991) Effect of the temperature conditioning on chilling injury of cucumber cotyledons. Plant Physiology. 95:443-449.

Lock H (1963) Catalase. In: Bergmeyer HU (ed) Methods of enzymatic analysis, vol 2. Verlag Chemie, Weinheim/Bergstr, pp 885–894.

Lopes AS, Silva MC, Guimarães GLR (1991) Correção da acidez do solo. São Paulo: ANDA. 22 p. (Boletim Técnico 1).

Malavolta E, Vitti GC, Oliveira AS (1997) Avaliação do estado nutricional das plantas: princípios e aplicações. 2.ed. ver. e atual. Piracicaba: Potafos, 2:319.

Martins CM, Martins SCS, & Borges, WL (2017). Correção da acidez, adubação e fixação bológica. *Embrapa Amapá-Capítulo em livro científico (ALICE)*.

Mauad M, Silva TLB, Neto AIA, Abreu VG (2010) Influência da densidade de semeadura sobre características agronômicas na cultura da soja. Dourados. MS,3:9:175-181.

Pauletti V, Pierri LD, Ranzan T, Barth G, Motta ACV (2014). Efeitos em longo prazo da aplicação de gesso e calcário no sistema de plantio direto. Revista Brasileira de Ciência do Solo. 38(2): 495-505.

Prado RM, Fernandes FM, Natale W (2001) Uso agrícola da escória de siderurgia no Brasil – Estudos na cultura da cana-de-açúcar. Jaboticabal, Funep, 68.

Pulz AL, Crusciol CAC, Lemos LB, Soratto RP (2008) Influência de silicato e calcário na nutrição, produtividade e qualidade de batata sob deficiência hídrica. Revista Brasileira de Ciência do Solo. 32:1651-1659.

Qi J, Song CP, Wang B, Zhou J, Kangasjarvi J, Zhu JK, Gong Z (2018) Reactive oxygen species signaling and stomatal movement in plant responses to drought stress and pathogen attack. J Integr Plant Biol. 60:805–826.

Raij B. van, Cantarela H, Quaggio JÁ, Furlani AMC (1997) Recomendações de adubação e calagem para o Estado de São Paulo. Campinas: IAC, 2:285 (Boletim Técnico 100).

Rheinheimer DS, Santos EJS, Kaminski J, Bortoluzzi EC, Gatiboni LC (2000) Alterações de atributos do solo pela calagem superficial e incorporada a partir de pastagem natural. Revista Brasileira de Ciência do Solo, Viçosa, 24:797-805.

Rosolem CA, Bessa MA, Amaral PG, Pereira HFM (1992) Manganês no solo: sua avaliação e toxidez de manganês em soja. Pesquisa Agropecuaria Brasileira, Brasília. 27:2:277-285.

Silva MA, Santos CM, Vitorino HS, Rhein AFL (2014) Pigmentos fotossintéticos e índice spad como descritores de intensidade do estresse por deficiência hídrica em cana-de-açúcar. Bioscience Journal. Uberlândia. 30:1:173-181.

Soil Survey Staff (2014) Keys to Soil Taxonomy, twelfth ed. USDA- United States Department of Agriculture. Vargas, J.P.R., Santos, D.R., Bastos, M.C., Schaefer, G., Parisi, P.B., 2019.

Souza MLC, Starling CDSAZ, Machuca LMR, Zuñiga EA, Galvão ÍM, de Jesus Guimarães J, & Broetto, F. (2020). Biochemical parameters and physiological changes in maize plants submitted to water deficiency. SN Applied Sciences. *2*(3), 1-9.