

Change in soil chemical attributes and yield of a common-bean crop in response to steel slag application

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Abstract

Most agricultural soils in Brazil are classified as acid, which limits agricultural production in the country, warranting the application of acidity correctives. The present study examined the effect of steel slag application on chemical characteristics of the soil as well as on the metabolic responses and yield of common-bean plants in a no-till system. The experiment was laid out in a randomized-block design with 42-m² subplots in a 7×2 factorial arrangement, with four replicates. Treatments consisted of two factors, namely, acidity correctives and application forms. The following correctives were tested: steel slag (T1), wollastonite (T2), ladle furnace slag (T3), stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control without correctives (C). The application forms were surface application and incorporation (20 cm). Ten months after the last reapplication of the acidity correctives, a soil probe sampler was used to collect samples from the 0–10 cm, 10–20 cm, and 20–40 cm layers for chemical analysis. The common-bean crop was established after 16 months of the applications, and the following parameters were evaluated 40 days after germination: plant height; leaf dry weight; relative water content; electrolyte losses; pigment content (Clo *a*, Clo *b*, and carotenoids); leaf macronutrient and micronutrient content; total soluble protein content; leaf silicon content; enzyme activities of superoxide dismutase, peroxidase, and catalase; and gas exchange. At the end of the crop cycle, grain production and yield components were evaluated. Phosphorus, pH, base saturation, and Si increased with the application of silicates, influencing the number of plants m⁻¹ and 100-grain weight; however, grain yield did not change.

Keywords: silicates, carbonate, silicon.

Introduction

In different regions of Brazil and the world, soil acidity is a limiting factor for crop growth and yield. The most frequently adopted measure for correcting soil acidity is liming. In Brazil, limestone is commonly used as an acidity corrective, and due to its poor solubility in water, its incorporation into the soil is recommended for greater efficiency (Kaseker, 2022). Besides limestone, steel slags can be a viable alternative for soil acidity correction.

The industrial expansion in recent years has generated large volumes of steel waste and by-products, one of which is steel slag. To mitigate the environmental consequences of the final disposal of this waste in landfills and reduce the cost of transporting it for disposal, steel industries have encouraged the sustainable use of slags in agriculture (Abrelpe, 2019).

In Brazil, the potential reuse of steel slags is approximately 32.1 million tons per year, according to the Annual Statistical Report of the World Steel Association (WSA, 2018). However, reuse of this byproduct in agriculture is still low—at around only 1%, whereas another 3% of its total amount is not reused, ending up in landfills (Brazil Steel Institute, 2017).

Soil acidity correction for subsurface layers is important in dry regions, where crop yield losses may occur. The great solubility and mobility of calcium silicate (SiO₃²⁻) in the soil profile makes it a viable alternative for the final disposal of steel slags (Hontoria et al., 2018), which can have a greater soil acidity correction power and provide more silicon (Si) to plants than limestone (Silva et al., 2021).

Common bean is classified as a Si non-accumulating plant, but this element can provide several benefits during plant growth and development, including greater resistance to pests and diseases, improved plant architecture, and increased resistance to biotic and abiotic stresses (Seidel et al., 2022).

In this study, we tested the hypotheses that i) steel slags can correct soil acidity with greater intensity than limestone, and ii) steel slags alter the plant's response to physiological and biochemical changes induced by biotic and abiotic stress factors in the common-bean crop. Therefore, the objective of this study was to examine the effect of steel slag application on the chemical attributes of the soil and the metabolic responses and yield of common-bean plants in a no-till (NT) system.

Results

Soil chemical characteristics

There was no interaction effect between soil acidity correctives and application forms on pH, Ca, Mg, or base saturation (Table 1). However, both factors affected these variables in isolation.

In terms of pH correction, in the 0–10 cm layer, steel slags (T1), wollastonite (T2), and ladle furnace slag (T3) were superior to control (C), which, in turn, performed equally to stainless steel slag (T4) and calcined agricultural limestone (T5) and did not differ from agricultural limestone (T6). At 10–20 cm depth, steel slag (T1) was better than calcined agricultural limestone (T5) and equal to T2, C, T3, T4, and T6. At greater depths (20–40 cm layer), T2 was superior to C and similar to T1, T3, T4, and T5, but differed from T6 (Table 1).

When each factor was analyzed separately, surface application had a significant effect on base saturation in the 0–10 cm layer, compared with incorporation (Table 1). The acidity corrective factor had a significant effect on base saturation (0–10 cm and 20–40 cm), Ca (20–40 cm), and Mg (all three analyzed layers).

Calcium levels increased with the application of T1, T2, T3, T4, and T5, compared with C, in the 0–10 cm layer. These correctives showed a similar behavior, differing from T6 (Supplementary Table 3). At the depth of 20–40 cm, T1, T2, T3, and T4 were superior to C, similar to T5, and different from T6.

Regarding the Mg levels, in the 0–10 cm layer, T1, T3, T5, and T6 were superior to C and differed from T2 and T4. In the 10–20 cm layer, T2 was superior to T4 and T5 and equal to T1, C, T3, and T5. Finally, at deeper layers, T6 was superior to C and similar to T3, T4, and T5, but differed from T1 and T2.

Considering base saturation under the acidity corrective factor, in the 0–10 cm layer, T1, T2, and T5 were superior to control and equal to T3 and T4, but differed from T6. At 10–20 cm depth, T1 was superior to T4, T5, and T6 and similar to T2, C, and T3. Finally, at 20–40 cm depth, T1, T2, T3, T4, and T5 led to higher base saturation values than C, differing from T6 (Table 1).

There was no interaction effect between acidity correctives and application forms on the organic matter (OM), P, S, or Si levels (Table 2). However, in the 10–20 cm layer, the interaction between factors influenced the S levels.

The application form influenced the OM, P, and Si levels up to the depth of 10 cm, with higher values achieved with incorporation (Supplementary Table 3). The acidity corrective factor affected the P and S levels in the 0–10 cm layer and Si levels in all three layers.

Regarding the influence of acidity correctives on P levels, in the 0–10 cm layer, T1 was superior to T3 and similar to C and T2, but differed from T4, T5, and T6. As for the S levels in the same layer, C was superior to T1, T2, and T4 and similar to T3, T5, and T6.

The acidity correctives had a significant effect on Si levels in the three soil layers (0 to 40 cm). At 0–10 cm depth, T1, T3, T4, T5, and T6 were superior to control and equal to T2. In the 10–20 cm layer, T4 increased Si levels in comparison to T1, T2, and T6, but was similar to C, T3, and T5. Finally, in the last layer (20–40 cm), T6 and T3 were superior to C, whereas T2, T5, and T6 did not differ from C.

In terms of S levels, considering the interaction effect between application forms and acidity correctives in the 10–20 cm layer, surface application had the same effect as all

correctives (Supplementary Table 3). However, among the incorporated treatments, C was superior to T1 and C but equal to T2 and T5 and different from T3 and T4.

Treatments T1, C, and T6 provided the lowest S levels in the 10–20 cm layer when applied on the soil surface (Supplementary Table 3), whereas the other correctives resulted in S levels that did not differ from each other.

Regarding cationic micronutrients (Supplementary Table 4), the application form only affected Mn levels at 0–10 cm and 10–20 cm depths and Cu levels at 0–10 cm depth, which were higher when the correctives were incorporated into the soil. Considering the effect of acidity correctives on Cu levels, at 0–10 cm and 20–40 cm, C was superior to all other treatments, except T3, which provided a Cu content statistically equal to that of control in the 20–40 cm layer.

At 10–20 cm depth, all treatments provided statistically equal Cu levels, except T3 and T2, which differed from each other.

There was an interaction effect between the application form and acidity corrective factors on the micronutrients Mn (0–20 cm), Fe (0–10 cm), and Zn (10–20 cm). However, the other variables were not affected by the interaction between both factors (Supplementary Table 4).

The interaction effect between application forms and acidity correctives was decomposed for the levels of Fe (0–10 cm), Mn (0–20 cm), and Zn (10–20 cm), as shown in Supplementary Table 7.

As regards Fe levels (0–10 cm), the decomposition of the interaction between factors showed that all treatments elicited the same response when incorporated and applied to the surface. When the correctives were incorporated into the soil, T2 provided higher Fe levels than T1 and C and similar levels to those provided by the other treatments. Surface application of T2 resulted in the highest Fe levels among all treatments.

When incorporated into the soil, at 0–10 cm and 10–20 cm depths, the treatments resulted in Mn levels that were statistically equal to or higher than those obtained with surface application, except for wollastonite, which provided higher Mn levels at 0–10 cm depth with surface application. Regarding the Mn levels in the 0–10 cm layer, the correctives showed the same behavior when incorporated except for T4, which provided lower levels than other treatments. With surface application, T2 provided higher Mn levels than the other treatments, especially T5 and T6. Similarly, at 10–20 cm depth, all correctives performed equally when applied by incorporation. However, when applied to the surface, C provided higher Mn levels than the other correctives, considering both factors.

The decomposition of the interaction between factors for Zn levels at 10–20 cm depth revealed that soil-incorporated T2 was superior to the other treatments. The same was observed for T2 when the acidity corrective factor was considered. However, surface application of T2 provided lower Zn levels than the other treatments. Considering the acidity corrective factor under surface application, T4 provided the highest Zn levels among all treatments (Supplementary Table 5).

Physiological, nutritional, and biochemical characteristics of common-bean plants

There was no interaction effect between the application form and acidity corrective factors on the analyzed variables (Supplementary Table 6). However, application form

influenced photosynthesis and stomatal conductance, which were higher with the incorporation of the treatments in the soil.

Considering the applied acidity correctives, only C had a significant effect on electrolyte loss (EL), whose values were lower than those seen with the other treatments and equal to those achieved with T4 and T6.

There was an interaction effect between acidity corrective and application form on the mean leaf Mg and Mn contents (Supplementary Table 7). For the other variables, there was no interaction effect. Application form had an isolated effect on the leaf levels of K, Ca, Mg, Mn, and Zn. Soil incorporation led to higher levels of Ca, Mg, Mn, and Zn, whereas surface application increased the leaf K content.

The acidity correctives had an isolated effect on the leaf levels of the macronutrients K, Ca, and Mg and the micronutrients Mn and Zn, as well as on the Si content. Regarding the K and Si levels, the effect of C was greater than those of all other correctives. As for Ca levels, the C treatment was only inferior to T3, whereas for Mg levels, T2 and T6 were inferior to the other correctives, including control. Manganese levels were higher with C than with all other treatments, which did not differ from each other. Considering Zn levels, C was superior to T1, T3, and T6 and similar to T4 and T5 but different from T2 (Supplementary Table 7). Control treatment provided the lowest leaf levels.

The decomposition of the interaction between factors for Mg and Mn contents indicated that, with the exception of T6 and T2, which were equivalent to control, all correctives elicited the same response when incorporated into the soil, producing higher Mg and Mn levels. Considering surface application, T1, T2, and C were inferior to T3, T4, T5, and T6 (Supplementary Table 8).

When incorporated into the soil, all acidity correctives had the same effect, producing lower Mg and Mn levels, compared with the control. When the acidity correctives factor was considered, all treatments generated similar results when applied to the surface. As regards Mn levels, the application form was an influential factor only in C, which produced much higher levels when incorporated.

There was an interaction effect between the acidity corrective and application form factors on the POD enzyme. For the other variables, there was no interaction effect. It should also be emphasized that the application form had an isolated effect on SOD activity, which was higher with the incorporation of the correctives than with surface application (Supplementary Table 9).

The acidity correctives only affected the activity of CAT, with T2 being superior to C, similar to T3, T4, and T6, and different from T2 and T5.

Stem dry weight was highest with the incorporation of T3 among all treatments. However, under surface application, this variable increased with T3 and the correctives T2 and T6, compared with T2, C, and T5.

Considering POD activity, the decomposition of the interaction between factors indicated that all correctives induced the same response when applied to the surface. Under incorporation, T2 and C induced a higher peroxidase activity. Treatments T2 and T3 resulted in higher POD activity than T1, C, T4, T5, and T6 (Supplementary Table 10).

Common-bean yield components

There was no interaction effect between soil acidity corrective and application forms for the components of the yield of common bean (Supplementary Table 11).

Considering the factors separately, only the acidity correctives induced a difference in 100-grain weight, whereas the other variables were not significantly affected.

Discussion

All acidity treatments corrected the soil pH values in the 0–10 cm layer, except for control and agricultural limestone, which provided soil pH values below 5.0.

In the field, fertilizer application and acidity correction for the surface layer of acid soils are relevant issues to be considered. However, the soil will remain in its natural condition in the subsurface layer, which frequently shows high Al saturation and low base saturation (Rossato et al., 2009), thereby compromising crop growth and development.

In the present study, only T2 exhibited medium active acidity concentrations in the 10–20 cm and 20–40 cm layers after 10 months of application. This can be explained by the greater difficulty in correcting soil acidity in deeper layers. Nonetheless, silicates are more reactive than limestone, causing soil correction to reach the 40 cm layer.

Thus, these reactions will only reach the deepest soil layers if the surface pH is around 5.5. In the current study, although the pH of the soil surface layer was corrected, the treatments containing silicates had a greater residual effect throughout the analyzed layers.

Treatments T2 and T4 provided low Mg levels in the soil, which can be explained by the low levels of this element in their composition.

Magnesium values ranged from 16 to 5 mmolc dm⁻³ in the surface layer (0–10 cm), 10 to 8 mmolc dm⁻³ in the 10–20 cm layer, and 3 to 2 mmolc dm⁻³ in the deepest layer (20–40 cm).

Considering soil acidity correction, the application of silicate correctives had a beneficial effect on Ca levels in the deepest layers. Although silicates have greater solubilization, the steel slag (T2) corrective was capable of correcting soil acidity in the surface and 0–10 cm layers. This increase may be due to the small particles of Ca and Mg that were present in the correctives and were sampled together with the soil and solubilized in the extraction process, becoming available as Ca²⁺ and Mg²⁺.

The higher Ca and Mg availability in the soils resulted in increased base saturation values at 0–10 cm and 20–40 cm depths after 10 months of application of the correctives, which were consistent with the Ca and Mg levels in the soil.

Organic matter values increased with surface application (0–10 cm) due to the remains of the previous crop on the soil surface and the lack of soil turning, which favored organic matter accumulation due to straw decomposition, causing the nutrients to be recycled.

Phosphorus levels in the surface layer varied from 32 to 16 mg dm⁻³ with T6 and from 22 to 12 mg dm⁻³ with T2, compared with C, but variations in this element were only significant under surface application. The higher P levels found with the control treatment can be attributed to its lower extraction by the plants, since crop development in this treatment was low, as influenced by the low pH.

Sulfur levels were higher in the deepest soil layers, ranging from 45 mmolc dm⁻³ in the surface layer (0–10 cm), obtained with C, to the lowest value of 18 mmolc dm⁻³, provided by T6. In deeper soil layers, such as 10–20 cm, the S level was high when incorporation was adopted as the application

Table 1. Mean values of pH in CaCl₂, Ca, Mg, and base saturation (BS) in the soil after 10 months of incorporated and surface application of steel slag (T1), wollastonite (T2), ladle furnace slag (T3), stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control treatment (C) without correctives.

Treatment	pH			Ca			Mg			BS		
	CaCl ₂			mmolc dm ⁻³			mmolc dm ⁻³			%		
	Layer (cm)											
Application (A)	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40
Incorporated	5.0 a	4.6 a	4.4 a	46 a	33 a	27 a	11 a	9 a	3 a	56 b	43 a	38 a
Surface	5.2 a	4.6 a	4.4 a	47 a	40 a	28 a	15 a	9 a	3 a	65 a	46 a	38 a
F	4.6 ^{ns}	0.0 ^{ns}	0.0 ^{ns}	8.5 ^{ns}	8.5 ^{ns}	2.3 ^{ns}	7.9 ^{ns}	0.4 ^{ns}	0.4 ^{ns}	11*	1.4 ^{ns}	0.0 ^{ns}
Corrective (C)												
C	5.4 a	5.0 a	4.4 ab	87 a	45 a	33 a	15 a	10 ab	4 bc	74 a	60 a	41 a
T1	5.5 a	4.8 ab	4.7 a	70 ab	41 a	32 a	12 ab	13 a	4 bc	74 a	49 ab	44 a
T2	3.9 c	4.5 ab	4.0 c	16 c	37 a	14 c	6 b	8 ab	1 c	20 c	44 ab	20 b
T3	5.3 ab	4.7 ab	4.5 ab	70 ab	40 a	34 a	15 a	10 ab	2 ab	66 ab	49 ab	44 a
T4	5.2 ab	4.5 ab	4.5 ab	60 ab	32 a	31 a	14 ab	7 b	3 ab	66ab	39 b	42 a
T5	5.5 a	4.3 b	4.6 ab	54abc	28 a	29 ab	16 a	7 b	3 a	70 a	35 b	44 a
T6	4.8 b	4.3 ab	4.3 bc	40 bc	32 a	19 bc	15 a	8 ab	3 ab	54 b	37 b	30 ab
F	24**	2.6*	6.0*	5.8**	0.8 ^{ns}	8.8*	3.0*	2.8*	6.8**	27.7*	2.0*	7.5**
A × C	1.0 ^{ns}	1.2 ^{ns}	0.5 ^{ns}	1.2 ^{ns}	0.4 ^{ns}	1.7 ^{ns}	0.6 ^{ns}	1.7 ^{ns}	0.7 ^{ns}	12 ^{ns}	1.1 ^{ns}	0.7 ^{ns}
CV (%) plot	7	11	8	48	45	35	35	46	29	16	29	45
CV (%) subplot	6	10	5	47	49	27	44	39	14	17	38	14

Means followed by different letters in the columns differ from each other by Tukey' test at 5% (*) and 1% (**) probability. CV: coefficient of variation.

Table 2. Organic matter (OM), P, S, and Si contents in the soil after 10 months of incorporated and surface application of steel slag (T1), wollastonite (T2), ladle furnace slag (T3), stainless steel slag (T4), calcined agricultural limestone (T5), agricultural limestone (T6), and a control treatment (C) without correctives.

Treatment	OM			P			S			Si		
	g dm ⁻³			mmolc dm ⁻³			mmolc dm ⁻³			mg kg ⁻¹		
	Layer (cm)											
Application (A)	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40	0-10	10-20	20-40
Incorporated	28 b	25 a	24 a	16 b	13 a	9 a	27 a	57 a	62 a	15 a	15 a	18 a
Surface	33 a	26 a	23 a	27 a	14 a	9 a	26 a	44 b	75 a	18 a	18 a	18 a
F	20*	0.4*	0.3 ^{ns}	18.3*	0.5 ^{ns}	4.2 ^{ns}	0.0 ^{ns}	27.5*	2.9 ^{ns}	1.4 ^{ns}	1.4 ^{ns}	0.0 ^{ns}
Corrective (C)												
C	30 a	27 a	25 a	27 ab	16 a	9 a	45 a	58 a	65 a	10 c	15 ab	14 c
T1	31 a	25 a	23 a	32 a	12 a	10 a	18 b	30 b	75 a	19 a	14 b	22 a
T2	32 a	23 a	23 a	22abc	12 a	9 a	21 b	38 ab	74 a	16 ab	14 b	16 bc
T3	32 a	25 a	25 a	16 c	13 a	9 a	25 ab	58 a	62 a	19 a	19 ab	21 a
T4	30 a	27 a	24 a	20 bc	15 a	8 a	22b	49 ab	63 a	19 a	21 a	19 ab
T5	31 a	26 a	23 a	18 bc	14 a	9 a	33 ab	65 a	73 a	20 a	15 ab	17abc
T6	31 a	26 a	22 a	17 bc	14 a	8 a	25 ab	53 ab	69 a	20 a	14 b	16 bc
F	0.8 ^{ns}	1.7 ^{ns}	1.8 ^{ns}	2.5*	0.4 ^{ns}	2.0 ^{ns}	3.1**	4.0**	0.4 ^{ns}	27.7*	2.0*	7.5**
A × C	1.0 ^{ns}	1.6 ^{ns}	0.8 ^{ns}	0.5 ^{ns}	0.6 ^{ns}	1.2 ^{ns}	1.1 ^{ns}	3.2*	0.3 ^{ns}	1.2 ^{ns}	1.1 ^{ns}	0.7 ^{ns}
CV (%) plot	14	5	5	36	45	28	12	18	41	30	25	45
CV (%) subplot	10	9	10	40	40	30	21	33	33	27	33	14

Means followed by different letters in the columns differ from each other by Tukey's test at 5% (*) and 1% (**) probability. CV: coefficient of variation.

form. The silicate correctives did not affect sulfate mobility, compared with the two limestones used in this experiment. Soil Si levels were around 15 to 20 mg dm⁻³ for all applied correctives, especially those containing silicates, except C and T5, which provided Si values below 15 mg dm⁻³. Si. Increased Si levels in the 20–40 cm layer were especially provided by the mobility of this element in the soil. After 10 months of application of the acidity correctives, there was an interaction effect between application forms and acidity correctives on the Mn level. All treatments generated similar values, except T2, which provided the lowest Mn levels (Supplementary Table 5). Ladle furnace slag (T3) provided higher Mn levels when the correctives were incorporated into the soil, whereas C resulted in the highest Mn levels

when applied to the surface. The availability of the nutrients Cu, Mn, Fe, and Zn is directly related to the soil pH, since their solubility increased when the pH was corrected. The high levels of these elements found in the control treatment are associated with the acidity of the soil, whose pH was 4.3 and 5.0. This pH range allowed an increase in the availability of these nutrients in the soil solution and favored their absorption by the plants. The turning of soil caused by the application of the correctives by incorporation, coupled with the crop remains on the soil surface, favored organic matter degradation and increased Cu availability in the soil surface layer.

The other variables analyzed in the three soil layers did not differ significantly between treatments. Mean K levels in

each layer were as follows: between 0.8 and 1.2 mmolc dm⁻³ at 0–10 cm, between 0.6 and 0.8 mmolc dm⁻³ at 10–20 cm, and between 0.4 and 0.7 mmolc dm⁻³ at 20–40 cm. Mean B values ranged from 0.3 to 0.4 mg dm⁻³ at 0–10 cm, 0.3 to 0.5 mg dm⁻³ at 10–20 cm, and 0.4 to 0.5 mg dm⁻³ at 20–40 cm.

Surface application of acidity correctives led to an increase both in photosynthesis (12.4 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and stomatal conductance (0.2 mol H₂M⁻² s⁻¹), compared with soil incorporation (Supplementary Table 5) In addition, the limestones and silicates showed no difference in terms of internal CO₂ concentration and transpiration under both factors analyzed in this study. Thus, the water absorption mechanism of the plants was more effective when the treatments were applied to the surface, resulted in the increased stomatal conductance found in this study. Considering the acidity corrective factor, the common-bean leaves also exhibited higher electrolyte losses, which ranged from 39 $\mu\text{g cm}^{-2}$ in T1, T2, T3, and T5, to 19 $\mu\text{g cm}^{-2}$ in C.

The leaf Fe contents were not within the range considered excessive for the common-bean crop. This increase can be caused by several factors, such as low pH, which result in greater availability of this micronutrient to the plants, possibly causing phytotoxicity (Camara, 2015), or the residual effect of Fe present in the applied correctives. On the other hand, the leaf Mn contents were within the range considered adequate for common bean, except in the control treatment (430 mg kg⁻¹), which showed high Mn levels. This increase in Mn levels induced the activation of antioxidant enzymes, which act as stress indicators, including SOD, CAT, and POD. It is also important to mention that the Si present in silicates can reduce the stress caused by an excess of a given element. The common-bean leaves that received the control treatment showed lower Si levels (2.6 g kg⁻¹) than those treated with the other correctives (above 5.0 g kg⁻¹). Therefore, in the present study, the use of silicates was efficient in supplying Si in the three soil layers, consequently favoring Si absorption by the plants. However, the silicates did not differ from the limestones. Although there was no statistical difference for grain yield, the acidity correctives acted positively on 100-grain weight (Supplementary Table 11). The low grain yield obtained in the current experiment is noteworthy.

For 100-grain weight, the corrective T6 resulted in 21 g, whereas the other treatments provided higher values, which ranged from 23 to 28 g. Thus, a possible difference in 100-grain weight did not influence yield. The excess of some nutrients, such as Fe and Mn, in the common-bean plants may have activated their defense mechanisms by oxidative enzymes, which caused the lower 100-grain weight seen with T6. Deus & Büll (2013) used the same correctives for a common-bean crop and also found no difference in yield between the two at 12 months after their application.

Material and methods

Description of the area and the soil

The experiment was carried out from August 2019 to May 2021 in a dystic Oxisol ('Red Latosol', according to the classification proposed by Embrapa (2018)), at the School of Agronomical Sciences, Sao Paulo State University (Unesp), located in Botucatu - SP, Brazil (22°51'15"S and 48°26'30"W, 740 m altitude). According to the Köppen classification system, the climate in the region is a Cwa type (tropical altitude climate, with dry winters and hot and humid summers) (Supplementary Fig 1).

Before the experiments were established, the site remained fallow for 20 years, covered with brachiaria grass (*Urochloa decumbens*), without any cultivation. The first experiment was established in 2010 and consisted of the application of acidity correctives on the soil surface or their incorporation with the aim of implementing the no-till system. Reapplications were carried out in 2013 and 2017, based on the chemical analysis of the soil at the time and the chemical characteristics of each corrective. For all applications, the rate was calculated so as to increase base saturation to 70%. Prior to the fourth application of the correctives, in 2019, thirty months after the third application, soil samples were collected from the 0–20 cm layer of each treatment for chemical characterization (Supplementary Table 1), according to the methodology described by Raji et al. (2001). The physical and chemical properties of the correctives (Supplementary Table 2) were determined according to the Brazilian Legislation for Limestones (Alcarde, 2009). The correctives were reapplied in October 2019, manually and by broadcasting. For incorporation, the soil was prepared by plowing and harrowing before reapplication; then, a mid-harrow was used to incorporate the treatments.

Experimental design and crop management

The experiment was laid out in a randomized-block design with split-plots of 42 m² (6 m × 7 m), with four replicates. The plots consisted of the soil acidity corrective application forms, namely, surface application or incorporation, whereas the subplots consisted of the following corrective materials: stainless steel slag (T4), agricultural limestone (T6), calcined agricultural limestone (T5), steel slag (T1), ladle furnace slag (T3), wollastonite (T2), and a control (C) without correctives. The corrective materials were in the form of ready-to-use powder for agriculture and were characterized (Supplementary Table 2.) according to Brasil (2006). Based on the results of soil chemical analysis and the characteristics of the correctives, the rate of each corrective reapplied to each subplot was calculated according to the base saturation method (Raji and Quajjio, 1983), with the aim of increasing soil base saturation to 70% in all treatments, except control. Before planting, common-bean seeds (Cultivar 'IAC-Imperador') were treated with the Standap Top fungicide/insecticide (70 mL c.p., 30 kg of seeds) (equivalent to 25 g a.i. Pyraclostrobin, 225 g a.i. Methyl thiophanate, and 250 g a.i. Fipronil) and inoculated with a liquid inoculant (70 mL Biomarhyzo - *Rhizobium tropici*). Sowing was performed on February 19, 2021, using 0.45-m spacing between rows and 12 plants per linear meter. For sowing fertilization, the 02-20-20 formulation was applied at 200 kg ha⁻¹, taking into account the analytical results of all treatments, except control, and adopting the recommendations by Raji et al. (1996). Topdressing was performed 30 days after plant emergence, with 44 kg ha⁻¹ N (ammonia sulfate).

Soil sampling, plant tissue, and chemical analyses

Sampling for soil chemical analysis was performed 10 months after the reapplication of the acidity correctives. Four subsamples were collected per subplot, using a soil

probe sampler, to form a composite sample from the 0–10 cm, 10–20 cm, and 20–40 cm layers. Soil chemical analysis was conducted according to the methodology proposed by Raij et al. (2001), whereas Si was analyzed based on the methods described by Korndörfer et al. (2004). The plants were harvested at full flowering (40 days after germination) to evaluate plant height; leaf and stem dry weights; relative water content (Barr and Weatherley, 1962); electrolyte losses (Lafuente et al., 1991); pigment content (Hiscox and Israelstam, 1979); leaf macronutrient and micronutrient contents (Malavolta; Vitti; Oliveira, 1997); total soluble protein content (Bradford, 1976); leaf silicon content (Korndörfer et al., 2004); enzyme activity of superoxide dismutase (Giannopolitis and Ries, 1977), peroxidase, and catalase (Lock, 1963); and gas exchange (photosynthesis, internal CO₂ concentration, stomatal conductance to water vapor, and transpiration rate). Readings were performed between 09h00 and 11h00 with a closed system composed of an infrared gas analyzer model LI-6400XT (LI-COR, Lincoln, Nebraska - USA), which allows recording gas exchange. At the end of the crop cycle, the number of pods per plant was determined by counting the total number of pods containing at least one grain. The number of grains per pod and 100-grain weight were also determined, with the data being later corrected to 13% moisture (wet base); and the plants at the useful area of each subplot were harvested manually. Manual harvest was performed 82 days after seedling emergence, and two 2-m rows per subplot were collected to calculate yield in t ha⁻¹, with grain moisture corrected to 13%.

Statistical analysis

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

Conclusion

The efficiency of the studied silicates in correcting soil acidity was similar to that of the limestones, regardless of the soil management system. Silicate application increased the pH, base saturation, P, and Si levels, as evidenced by 100-grain weight, but did not influence the yield of the common-bean crop. Surface application of acidity correctives increased photosynthesis and stomatal conductance in the common-bean plants. The common-bean plants showed high Fe levels with all treatments and high Mn levels only with the control treatment, which induced the activation of the SOD, POD, and CAT enzymes, which act as stress indicators.

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Declaration of Competing Interest

The authors have no conflicts of interest to declare.

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