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APPLICATION OF STEEL SLAG IN PASTURE OF *Urochloa brizantha* IN THE AMAZON

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ABSTRACT

Steel slag is a residue from the production of pig iron (steel industry), which has Si in its composition, in the form of calcium and magnesium silicate. It has the potential to correct soil acidity, and can also be used as a silicate fertilizer. The objective of this study is to evaluate the application of slag in *Urochloa brizantha* pasture at different doses and its effects on the plant. However, for the use of the different slags, they must initially be chemically characterized. Once the one with the greatest potential to be used as silicate fertilizer was chosen, a randomized block experimental design was established in the field, with four replications, and the treatments consisted of four doses of selected slag (0, 200, 400 and 600 kg $^{ha-1}$). Subsequently, the morphophysiological responses were evaluated. The highest concentration of Si was found in blast furnace slag (atomic absorption spectrophotometer), which was used as silicate fertilizer. The application of the slag was manual and in cover after lowering the pasture. Before flowering, young and adult leaves were removed from the plots with and without the maximum dose. The samples were processed according to techniques for scanning electron microscopic analysis and spectroscopic microanalysis of x-rays by energy dispersion. The higher dose provided an increase in the number of siliceous bodies and the Si content in aculeiform tector trichomes in the leaf blade, as morphophysiological responses of the same in the face of the high availability of the element in the soil. The dose that provided the best performance was between 200 and 400 kg $^{ha-1}$.

Keywords: Silicon. Brachiaria. Silica deposition. Silicose bodies. Trichomes.

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INTRODUCTION

Silicon is one of the most abundant elements in the Earth's crust, surpassed only by oxygen, being part of the composition of most minerals, being present, in greater or lesser quantities, in practically all types of soils (Silva; Bohnen, 2001). Si, through silicate fertilization, even though it is not considered as an essential element, can allow an induction of temporary resistance in *Urochloa brizantha* plants to the attack of certain insects, becoming a beneficial element for plants.

As is known, some species, especially grasses, have the ability to accumulate silicon in plant tissue, especially in the cell wall, giving these plants a greater structural resistance to their cells (Soratto et al., 2007). Practically, all the absorbed Si is translocated from the roots to the leaves and, with the exit of water through transpiration, it polymerizes on the outside of the cell wall (mainly in the cells of the epidermis), transforming it into an amorphous silica mineral (Silva; Bohnen, 2001). This process of silification of epidermal cells would work as an effective physical barrier against insect attack, reducing the damage caused by the occurrence of pests (Silva; Bohnen, 2001).

Thus, the accumulation of Si in the aerial part can contribute to a greater resistance of *Urochloa* plants to attack, for example, by leafhoppers in pastures. Many studies demonstrate its importance for several other crops, especially rice and sugarcane (Pereira et al., 2003). The induction of temporary resistance in plants has good prospects, mainly because it is lower cost and causes less environmental impact than the use of insecticides (Albuquerque et al., 2007). This resistance induced in plants by the presence of silicon, in a practical and economical way, can be obtained through the application of chemical or mineral products, such as the use of steel slag. Various slags have been applied in agriculture to supply plants with Si on several continents. However, few studies have been carried out in Brazil to verify the viability of these by-products.

Around the world, industrial activity generates solid waste that can pose risks to the environment. Due to these environmental risks, it is necessary to define an appropriate destination for this waste, and if possible to use it in other activities essential to man (Prado; Fernandes, 2001). The use of industrial and urban waste in agriculture as a source of nutrients or as acidity correctives is a trend resulting from the need to minimize the harmful effects of nutrient accumulation in production centers (Marciano et al., 2001). As long as it has corrective or fertilizer characteristics and does not contaminate the soil and water sources, any by-product or residue can perfectly be used in agricultural activities (Araújo et al., 2007).

In the smelting processes of iron ore for the production of pig iron and steel, a large amount of slag and other solid residues are resulting (Prado; Fernandes, 2001). Thus, steel slag can come from different industrial processes. Therefore, each waste generated must have different levels of calcium and magnesium silicate in its composition, which give it different corrective properties for soil acidity (Prado et al., 2007), as well as for the availability of silicon to plants. Thus, the use of alternative materials such as steel slag can help improve soil fertility and the growth of cultivated pastures, with a consequent increase in the production of dry matter of forage grasses.

DEVELOPMENT

CHARACTERIZATION OF THE CHEMICAL COMPOSITION OF SLAG FROM DIFFERENT STEEL PROCESSES IN THE STATE OF PARÁ

Brazil produces an average of 3.5 million tons of pig iron, of which about 24% comes from steel mills in the states of Pará and Maranhão, which together account for the second largest production in the country (Brasil, 2017). The steel industry represents an important segment of the economy of Pará and has the production of pig iron as one of its highlights, since the state is one of the largest producers in the country (Brazil; Nascimento, 2019). Slag is the main waste generated in the pig iron production process and has often been accumulated in the yards or landfills of industries, causing environmental problems (Brasil; Nascimento, 2019).

Worldwide, industrial activity generates solid waste that can pose risks to the environment (Coelho, 2013). For this reason, it is necessary to define an appropriate destination for this waste and, if possible, to use it in other activities essential to man (Prado; Fernandes, 2001). The use of industrial waste in agriculture as acidity correctives or as a source of nutrients is a trend resulting from the need to minimize the harmful effects of accumulation in production centers (Marciano et al., 2001). Thus, as long as it has corrective or fertilizer characteristics and does not contaminate the soil and water sources, any waste can perfectly be used in agricultural activities.

The steel park of Marabá / PA has as its main production the manufacture of pig iron, but there is also industry carrying out refining (steel mill). In this way, there is the possibility of making use of the different residues (slag), from the steel process, in agriculture. In the smelting processes of pig iron and steel, a large amount of slag is a by-product as solid waste (Prado; Fernandes, 2001). Of the total pig iron produced, 10% to 15% of slag is generated (Prado et al., 2001), which is often accumulated and with an uncertain destination, generating a serious environmental problem (Sobral et al., 2011). In general, steel slag, in addition to having Si in its composition, is chemically constituted by calcium and magnesium silicate, which can give it a corrective property of soil acidity similar to that of limestone (Prado; Fernandes, 2001). However, in Brazil, slag is still little used in agriculture, even with the reduction of natural nutrient reserves and the high costs of fertilizers and correctives (Prezotti; Martins, 2012).

Silicon in the Earth's crust is only surpassed by oxygen, being part of the composition of most minerals, being in practically all types of soils (Silva; Bohnen, 2001). Si is not considered an essential element for plant life, although many studies demonstrate its importance for various crops as a useful and enhancer element. The use of steel slag, for the purpose of silicate fertilization, increases the absorption of essential nutrients, provides tolerance or resistance of plants to pest attack, reduces transpiration and improves photosynthesis (Ma; Yamaji, 2006).

The composition of the slag varies as a result of the chemical constitution of the raw material and the different steelmaking processes. Therefore, the chemical characterization of the different types of slag from the steelmaking process is the first most important information to define its correct indication, either as an alternative corrective material or as a silicate fertilizer, helping, in both cases, to improve soil fertility and consequent increase in plant productivity. In Pará, there are few studies on the use of steel mill waste as an agricultural input (Brasil; Nascimento, 2019), which led to the development of this research.

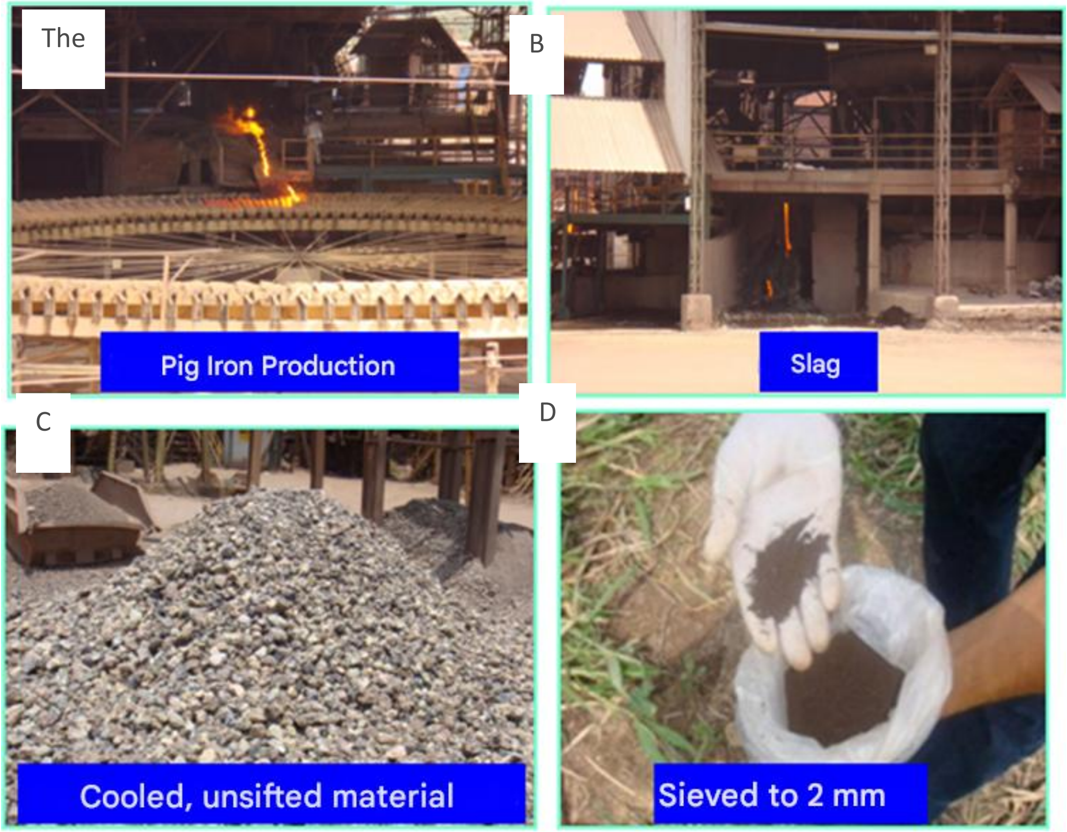
The present study, at first, aimed to characterize the chemical composition of three types of steel slag produced by a steel mill in the municipality of Marabá/PA, aiming at the best disposal of industrial waste for use in agriculture as an acidity corrective and/or as a silicate fertilizer, which will be used in the next work.

Methodology

After previous contact with the steel mills of the steel pole in the city of Marabá / PA, a technical visit was made to the largest steel mill in the region that processed the iron ore extracted from the municipality of Parauapebas / PA, which is located in the largest mineral province in the world; Serra dos Carajás, notably with regard to iron extraction. This steel mill had the so-called integrated production, in which the steelmaking process consists of three stages (reduction, refining/melt shop and forming: casting, rolling and drawing). From these stages in the production process, a sample of slag was collected from 1 – Blast Furnace; where the transformation of Fe ore into pig iron occurs, a sample of slag from 2 – Electric Furnace; where the mixture of pig iron, scrap iron and lime and slag sample from 3 - Ladle Kiln occurs; whose function in refining is to lower the impurity content.

Pig iron is a type of cast iron produced from iron ore in equipment called a blast furnace. In Figure 1 it is possible to observe in a simplified way the leakage of slag, which is the main waste generated during the pig iron production process. Due to its insolubility and lower density, the slag is overgrown in pig iron and is conducted through channels to a proper place of cooling. This slag is the result of the mixture of ore gangue (SiO_2, Al_2O_3), fluxes (CaO, MgO) and charcoal ash, which provides high levels of silica (SiO_2) and calcium oxide (CaO), as well as oxides of aluminum (Al_2O_3), magnesium (MgO) and iron (FeO) oxides (Brazil; Nascimento, 2019).

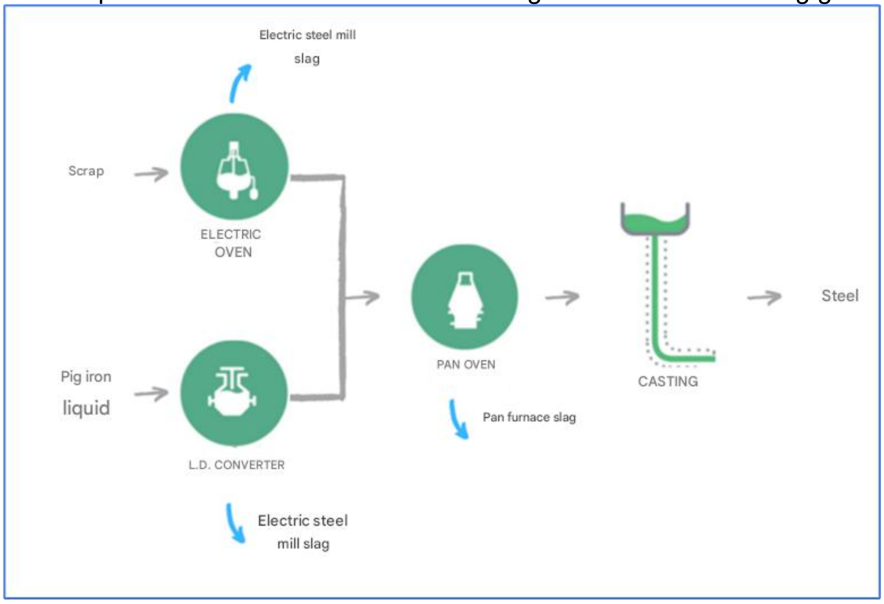
Figure 1. General aspect of the processing of iron ore to pig iron (A), leakage of slag as residue (B), cooling of the residue (C) and presentation of crushed and sifted slag (D), from a steel mill in the region of Marabá / PA



Source: Prepared by the authors on a technical visit to the steel mill to collect slag samples.

Figure 2 shows the simplified beneficiation scheme of a steel mill with integrated production, immediately after blast furnace processing seen in Figure 1. In a logical sequence, we have the so-called electric arc furnace and the oxygen melt shop, whose basic functions of these equipment are to transform pig iron and scrap into liquid steel, generating as a by-product the so-called steel mill or electric furnace slag. Continuing the integrated industrial processing, there is the ladle furnace, which makes the interface between melting and casting, also generating another by-product called ladle furnace slag. Ladle furnace slag is also known as reducing refining slag, which is generated by adding deoxidizers and lime to eliminate oxygen and sulfur from liquid steel and adjust the composition of the steel by adding ferroalloys (Mendes, 2016). These three slags mentioned above are poured in a yard and/or discharged in places where they can cool and solidify into crystalline form, for later crushing. It is noteworthy that oxidizing and reducing refining slag, as is the case of ladle furnace slag, differ from reduction slag, from blast furnaces, because they actively participate in the process, while the latter incorporate impurities (Geyer, 2001).

Figure 2. Simplified scheme of electric furnace slag and ladle furnace slag generation



Source: Presented by Geyer (2001).

The first characterization of the chemical composition of the slags from the different steel processes (1 – Blast Furnace; 2 – Electric Furnace; and 3 – Ladle Furnace), were carried out from a historical average of determinations regarding the contents of SiO2, CaO, MgO, NaO, K2O, NaO, P2O5, S, FeO, Al2O3, MnO, TiO, V2O5, F and Cr2O3, made and supplied by the steel company itself. As a routine practice, it already performs some determinations of the above elements, through daily readings, using an atomic absorption spectrophotometer. In the present work, these data were processed, determining the average percentage concentrations of the elements contained in the steel residues, as well as their standard deviations and coefficients of variation.

During the technical visit, in addition to the data obtained from the steel mill itself, samples of the three slags were collected after cooling and crushing. In the company's yard, for each specific slag heap, five different collection points (simple samples) were removed from the middle of the mounds, which together and mixed formed the composite samples referring to each of the slags studied. Before being sent for laboratory analysis, they were only sieved through a sieve with a 2.0 mm mesh (ABNT nº.10 Mesh), following the methodology described by (Embrapa, 1999), so that the slags reached a granulometry similar to that of agricultural correctives Commercial (Brasil, 2006), and that they could be determined by silicon (Korndörfer et al., 2004). Thus, after tamisation, the collected samples were properly packaged, and sent for some determinations.

In the fertilizer and corrective laboratory belonging to the Faculty of Agrarian Sciences (FCA), of the State University of São Paulo (UNESP), Botucatu Campus / SP, granulometric analyses and chemical analysis of alkaline reaction in the slags were carried out. The reactivity rate (RE) was determined, based on the particle size of the particles, its neutralization power (PN), based on the chemical purity of the original material, and the relative total neutralization power (PRNT) was calculated, which is the result of multiplying RE x PN, divided by 100. For limestone, the PRNT is an index to be used to determine the amount of corrective to be applied to the soil to reduce acidity.

At the same time, the samples were also sent to the Scanning Electron Microscopy Laboratory of the Emílio Goeldi Museum of Pará (MPEG), to obtain electromicrographs and perform microanalyses by Energy Dispersive Spectroscopy (EDS). In this case, for the spectroscopic microanalysis of x-rays by energy dispersion (EDS) and to obtain electromicrographs, the samples were adhered on metal supports through double-sided carbon tape. The microanalyses were performed with a Gresham de Si (Li) X-ray detector, model Sirius 10/7.5, with a resolution of 133 eV and Be window, a Q-500 digital signal processor and IXRF's own software, coupled to a scanning electron microscope (SEM) model LEO 1450 VP. Electronic acceleration and working distance of 20 Kv and 15mm, respectively, were used. The electromicrographs were obtained in the same SEM, operating under the same conditions as the EDS analyses. 5 points of 5 samples were evaluated for each of the three slags.

Results and Discussion

Chart 1 presents the results of the chemical characteristics of steel slag, determined by the steel company itself, based on a historical average of analyses, in order to identify its potential for the use of these industrial wastes. In this regard, in Brazil, there is still a lot of resistance regarding the use of industrial waste, despite Law No. 12,305/2010, which instituted the National Solid Waste Policy, which deals with the prevention and reduction of solid waste generation, with a set of instruments that allow for increased recycling and reuse of this waste (Brasil; Nascimento, 2019).

Table 1. Chemical characterization of steel slag from blast furnace, electric furnace and ladle furnace, obtained from a steel mill that had integrated production in the region of Marabá / PA

	SiO2	Dog	MgO	K2O	Not	P2O5	S
	%						
***Blast Furnace Slag* (1)**							
Average	41,44	25,86	4,15	3,82	0,33	3,06	0,09
DP*	1,20	2,33	1,10	1,38	0,02	0,98	0,02
CV (%)	2,90	9,02	26,59	36,22	6,46	31,94	18,55
1) Historical series of 21 observations							
***Electric Furnace Slag* (2)**							
Average	30,40	48,76	8,96	0,03	0,03	9,41	0,26
DP*	4,94	8,91	1,91	0,02	0,04	8,15	0,35
CV (%)	16,25	18,28	21,33	74,49	151,69	86,65	133,78
2) Historical series of 87 observations							
***Ladle Furnace Slag* (3)**							
Average	17,97	24,07	9,16	0,07	0,13	0,28	0,03
DP*	2,65	2,87	1,35	0,03	0,06	0,05	0,00
CV (%)	14,73	11,93	14,77	46,12	43,23	18,44	14,68
3) Historical series of 203 observations							

	FeO	Al2O3	MnO	V2O5	Uncle	F	Cr2O3
	%						
***Blast Furnace Slag* (1)**							
Average	0,20	18,53	4,11	0,18	0,70	-	-
DP*	0,27	1,33	0,89	0,00	0,05	-	-
CV (%)	135,54	7,19	21,75	2,29	7,83	-	-
(1) Historical series of 21 observations							
***Electric Furnace Slag* (2)**							
Average	4,91	4,24	3,06	0,18	0,36	0,21	0,03
DP*	8,84	1,21	3,13	0,01	0,12	0,51	0,06
CV (%)	179,91	28,47	102,43	5,80	32,51	244,4	195,24
(2) Historical series of 87 observations							
***Ladle Furnace Slag* (3)**							
Average	43,92	4,18	4,59	0,22	0,70	0,83	0,18
DP*	7,12	0,66	0,49	0,00	0,09	0,28	0,14
CV (%)	16,21	15,74	10,68	1,65	13,15	33,76	73,88
(3) Historical series of 203 observations							

*Standard deviation, considering a significance level of 5%
Source: Prepared by the authors based on historical data provided by the steel company studied, in a sequential period of approximately 2 months of analysis of the slag leaked during the industrial production process

The reuse of waste, such as those presented in Chart 1, is undoubtedly fundamental, whether from an economic or environmental point of view, and often from a social point of view (Sobral et al., 2011), because different slags are discarded daily in the form of solid waste in the yards of steel mills without a pre-defined destination. This environmental problem could be mitigated with part of its destination for use in agriculture, as a corrective of soil acidity and, or supplier of nutrients to plants, notably silicon, as long as the risks of contamination that they can cause are evaluated.

The chemical characterization of these residues can give an idea of the possibility of soil contamination (Chart 1), where few research studies in Brazil, for example, have evaluated the bioavailability of heavy metals by the application of slag to the soil (Brasil; Nascimento, 2019). In the three slags characterized in the study, iron (Fe) and manganese (Mn) had low concentrations available in the form of oxides to be able to cause problems such as heavy metals (Chart 1). Some studies with steel mill slag have presented results that indicate concentrations of heavy metals below the levels established by legislation. Even with the application of a high dose of slag in the soil (4.0 t $^{ha-1}$) (Coelho, 2013), only traces of the elements Fe and Mn were found in the soil, which did not constitute contamination. It should be remembered that these heavy metals (Fe and Mn), when they meet the criteria of essentiality to plant nutrition in terms of the amount available, start to act as micronutrients, that is, essential elements for plant life, but in small quantities.

Chromium (Cr), another heavy metal, was not even identified as a trace element in the three slags analyzed (Chart 1), and was not a problem. Likewise, the presence of fluorine (F) in steel slag was not found (Table 1), an ametal that can cause phytotoxicity in excessive concentrations. Other trace elements that could cause potential concern, such as sodium (Na), vanadium (V) and titanium (Ti), also showed low amounts (Chart 1), not being considered dangerous to Earth systems (Coelho, 2013). All the trace elements identified in Table 1 are present in relatively low concentrations, which in soils, plants and waters may or may not be essential for the growth and development of plants and animals.

Also considering the potential of steel slag as suppliers of macronutrients, essential elements for life required in greater quantities for plants, in Chart 1 the slags presented very low values of phosphorus (P205), potassium (K2O) and sulfur (S), not being characterized as a material with potential for the supply of these nutrients to the plants, as reported by (Coelho, 2013). On the other hand, the residues have relatively high concentrations of calcium (Ca), being in greater quantities for blast furnace slag and electric furnace slag, respectively (Chart 1). Magnesium (Mg) (Chart 1) presented much less expressive values than Ca. Mg concentrations were similar between electric furnace slag (8.96) and ladle furnace slag (9.16), where if rounded values are presented, without decimal places, there would be no difference. These values are more than double the value found for blast furnace slag (4.15).

Silicon, in the form of silicon dioxide (SiO2), was also identified in high concentrations in the residues, with greater prominence, in descending order, in the slag of blast furnace, electric furnace and ladle furnace, the latter having less than half of Si than the blast furnace slag that presented the highest quantity (Chart 1). These high concentrations of total SiO2 observed in the slags, indicating the possibility that the residues could be used as sources of Si for plants. Si, although not classified as an essential element for plant life, plays an important role in plant-environment relations, as it can provide certain crops with better conditions to withstand climatic, edaphic and biological adversities, with the final result being an increase and higher quality in production (Ma;

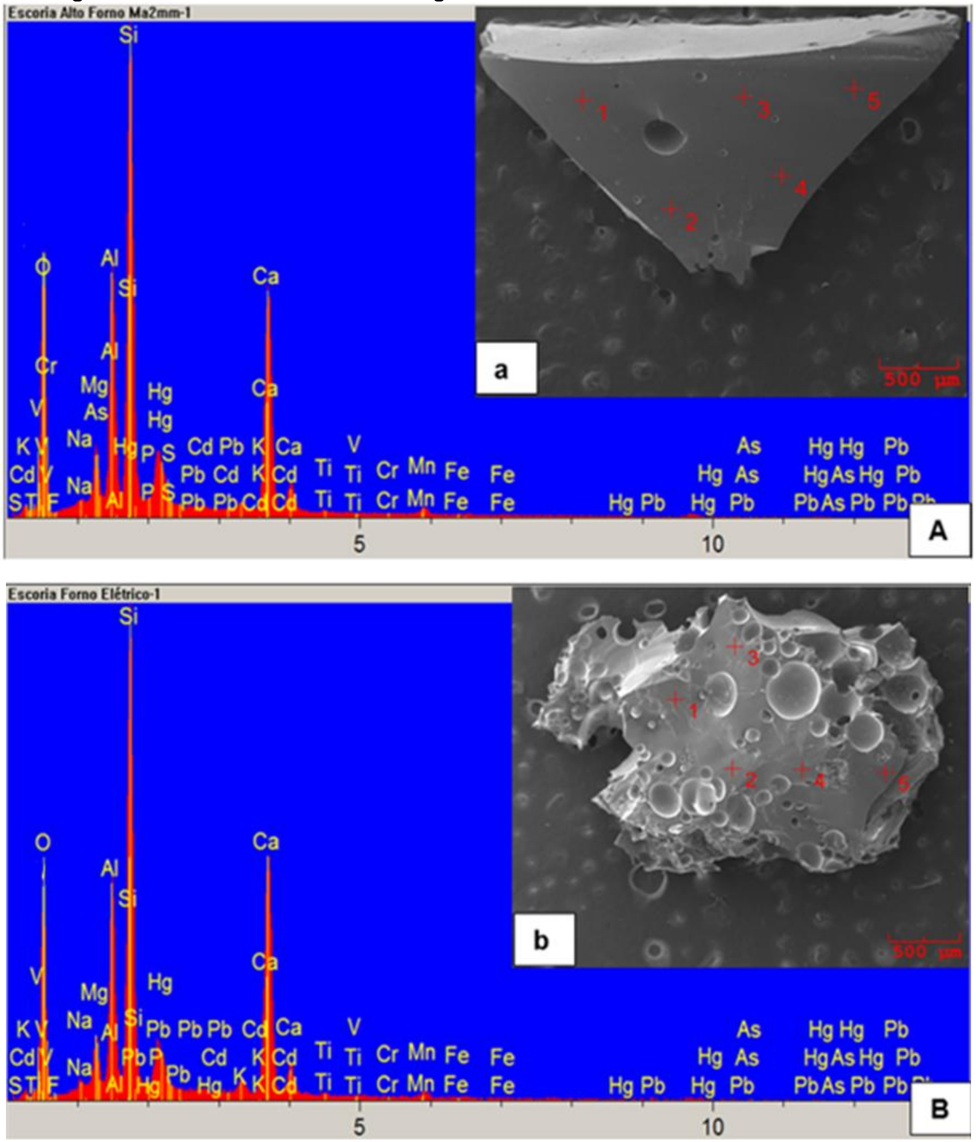
Yamaji, 2006). Stresses caused by extreme temperatures, summers, heavy or toxic metals, for example, can have their effects reduced with the use of Si. Benefits of the use of Si are manifested not only in plants known as accumulators (rice, sugarcane and pasture), but also in non-accumulator plants, such as tomatoes and plants from the Cerrado vegetation (Brazil; Nascimento, 2019).

Because they have constituents that neutralize soil acidity and bases such as calcium (Ca), magnesium (Mg) and silicon (Si) (Table 1), slag has potential for agricultural use as an alternative to limestone, especially in regions that have few deposits of agricultural limestone in exploitation, as is the case of the state of Pará (Vidal; Prado, 2011), or when most of the extracted limestone is destined for the manufacture of cement (Correa Neto et al., 2024). In addition to the corrective characteristics of acidity, due to the chemical composition of the slag, the high levels of SiO2 also denote the capacity to supply Si to the plants (Chart 1). However, as the Marabá steel plant in Pará, for the most part, is made up of non-integrated plants, where the manufacturing process consists of only one stage, notably the manufacture of pig iron, there is a greater availability of slag from the Blast Furnace.

Therefore, due to its greater availability and its chemical characteristics, such as the highest concentration of SiO2 and the second highest concentration of CaO, blast furnace slag was selected for a better evaluation of its potential not only as a silicate fertilizer, but also as a soil acidity corrective. Also, the present work deepens the evaluations for electric furnace slag, due to its highest CaO content and second highest SiO2 content. Ladle furnace slag, due to the lower volume available in the region and with the lowest concentration of Si (Chart 1), was not considered in the analyses to evaluate its potential for soil acidity correction. It is known that naturally ladle furnace slag, due to the fact that it has the function of refining, only lowers the concentration of impurities of what has already been previously processed in the electric furnace, justifying some of its lower values presented (Chart 1).

With the spectroscopic microanalysis of x-rays by energy dispersion (EDS) and obtaining the electromicrographs of the two slags selected for these analyses, it is possible to verify in Figure 3 that the highest absorbance peaks were for Si, Ca and Al, respectively, which correspond to the high average concentrations of these elements also detected in the samples analyzed by the steel company (Chart 1). The high peaks of oxygen (O) indicate that the elements are in the form of oxides. It should be noted that absorbance is directly proportional to concentration. Therefore, this justifies why the results presented in Figure 3 corroborate those observed in Chart 1, regarding the concentration of the elements contained in the blast furnace and electric furnace slag. The spectra and scanning electromicrographs refer to point 1 of samples 1 (Figure 3).

Figure 3. Spectra of EDS analyses (a-b) with the respective scanning electromicrographs (a-b) of steel slag. A and A: Blast furnace slag; B and b: Electric furnace slag



Source: Prepared by the authors based on the original research results

The higher concentrations of silicon found in blast furnace slag and electric furnace slag (Figure 3), respectively, characterize these materials as having high potential for use as silicate fertilizer. Thus, considering Normative Instruction No. 5, of February 23, 2007 (Brasil, 2007a), the two slags evaluated, as they present concentrations of total Si and Ca above 10% (Chart 1), can be classified as silicate slag fertilizers, also presenting characteristics of soil acidity corrective, which need to be better studied. However, the combination of these benefits must not jeopardise environmental quality, more specifically that of the soil. As observed in Chart 1 and Figure 3, there are also considerable concentrations of $Al2O3$ (aluminum oxide), which should not be neglected, especially in tropical soils where they predominate in the clay fraction, because when there is the formation of Al^{3+}, it is toxic to plant roots and a source of acidity in the form of H^+ ions produced.

As a reference parameter for other corrective products, in addition to agricultural limestone, the sum of Ca and Mg oxides (CaO + MgO) is analyzed, and it is possible to infer whether a residue from the steel industry has chemical properties for use as a material to correct soil acidity. In this sense, it can be seen in Chart 1 that only the slag from the electric furnace presented a sum of Ca + Mg equal to 57.72%, above the minimum requirement of 38% established by the Brazilian legislation on correctives (Brasil, 2007b). The higher concentration of calcium oxide and the sum of CaO + MgO presented by the slag from electric furnace is probably due to the fact that in this furnace, for the melting process, in every 1 ton of pig iron and iron scrap, approximately 40 kg of lime are used, responsible for the formation of slag in the capture of impurities in this bath. Blast furnace slag, with CaO + MgO equal to 30.01% and ladle furnace slag equal to 33.23%, despite indicating a good potential for soil acidity correction, for these values below 38%, would limit the registration of these residues in the Ministry of Agriculture, Livestock and Supply (MAPA), as soil acidity correctives, alternatives to the use of agricultural limestone.

The reaction of neutralization of soil acidity provided by the application of slag occurs by the dissociation of $CaSiO_3$ and $MgSiO_3$ into Ca, Mg and SiO_3. Calcium silicate is 6.78 times more soluble than calcium carbonate, which is present in limestone (Alcarde, 1992). SiO_3 is the one that reacts with the H^+ of the soil solution to form H_4SiO_4, thus reducing its acidity. Like limestone, the reactivity of slag varies according to its granulometry in contact with the soil (Prezotti; Martins, 2012). Thus, the granulometric analysis of blast furnace and electric kiln slag was carried out (Table 2), in the same way as it is done for limestone. The percentages of slag particles passing through three sieves (ABNT nº 10, 20 and 50 Mesh) were analyzed, used in comparison with what the legislation in force requires for agricultural limestone (Brasil, 2007b). The two selected slags obtained more than 95% of their particles by passing through sieve number 10 (2 mm) (Table 2). Only blast furnace slag presented more than 70% of particles passing through the sieve number 20 (0.84 mm), as recommended by the legislation for limestone. However, the last granulometric criterion was not met for any of the slags, which was the need to have at least 50% of the particles passing through the sieve number 50 (0.30 mm). These particles with a particle size of less than 0.30 mm would characterize for limestone a reactivity rate equal to 100 in a short period of 3 months of reaction in the soil.

Table 2. Percentage of particles passing through sieves used in the determinations of reactivity, neutralization power and relative total neutralization power, for characterization of acidity corrective material of the soils of steel slag, from blast furnace and electric furnace obtained from a steel mill in the region of Marabá / PA

Sample	% pass through the Sieves*			**Results in %		
	Pen10	Pen 20	Pen 50	RE	PN	PRNT
Blast Furnace Slag	99,97	78,07	40,77	67,53	50,00	34,00
Electric Furnace Slag	99,98	69,90	34,07	61,58	52,00	32,00

*Material passed through three sieves of different granulometries; ABNT No. 10 Mesh = 2.0 mm; ABNT No. 20 Mesh = 0.84 mm; and ABNT No. 50 Mesh = 0.30 mm
** RE = reactivity; NP = neutralizing power; and PRNT = Relative Power of Total Neutralization.
Source: Prepared by the authors based on the original research results

The current legislation (Brasil, 2006) also requires as reference parameters to classify industrial solid waste as other acidity correctives, in addition to limestone, minimum values of relative neutralization power - PN of 67% and relative total neutralization power - PRNT of 45%, for its use as soil corrective. For the two slags analyzed (Chart 2), it is verified that the PN values are lower than 67% and those of PRNT are lower than 45%, not meeting the standards determined by the legislation (Brasil, 2006). Although the minimum guarantees were not met (Table 2), the PN values (neutralization power in % of CaCO3 equivalent) were above 50% and the PRNT values were above 32% for the two residues, indicating that the slags have a high potential for correcting soil acidity, even though it was not possible to obtain registration from the Map for commercialization as a corrective product.

In the aforementioned context, it is possible to industrially make adjustments to the steel slag residue so that it has a product with the necessary parameters currently required to be classified as a corrective material for soil acidity. As the PRNT comes from the multiplication of the NP by the reactivity - RE of the corrective, divided by 100 (Chart 2), it would only be possible to change the RE of the slags (degree of fineness), in what deals directly with its granulometry. The NP, on the other hand, as it concerns the chemical purity of the source material, cannot be changed without chemical additives.

Thus, before the analyzes carried out, as the leaks of steel slag studied here, after cooling, were only crushed in a hammer mill and tamisation in a 2 mm sieve (ABNT nº 10 Mesh), new studies could be carried out increasing the degree of grinding of these materials, mainly with the use of ball mills that would have the ability to increase the degree of fineness and consequently increase the percentage of particles passing through the sieve of 0.30 mm (ABNT nº 50 Mesh), with an increase in RE close to 100%. The increase of the RE to an adequate granulometry will also allow the increase of the PRNT values above 45%, which is the minimum required to accept slag as a corrective material for soil acidity, such as agricultural limestone. With greater crushing, it would be necessary to carry out new chemical characterization analyses of steel slag regarding the availability of SiO2, CaO and MgO. In addition, studies to identify insoluble residue levels (IR = 12% to 41%) would be important because they may limit the achievement of higher values of NP and PRNT, respectively.

The possibility of using slag as a corrective and fertilizer is highlighted with the growing expansion of the steel industry and with the greater difficulties in acquiring limestone and fertilizers due to the prices of products plus freight (Sousa et al., 2025). The current trend, however, is to become increasingly difficult and costly for farmers to obtain limestone, due to its use in more profitable industrial sectors, such as cement manufacturing (Correa Neto et al., 2024). In regions where the occurrence of limestone deposits is reduced, the use of slag in agriculture represents a very interesting way of using this residue, which could be used as a corrective of soil acidity and a source of calcium, magnesium and silicon for crops (Brasil; Nascimento, 2019). Therefore, the use of alternative sources of materials that have corrective quality of acidity and fertilizer and that are often cluttered in the yards of steel mills can be a solution not only for their disposal, in the case of industries, but also in the sense of reducing agricultural production costs (Coelho, 2013).

MORPHOPHYSIOLOGICAL RESPONSES OF UROCHLOA BRIZANTHA CV. XARAÉS AFTER APPLICATION OF STEEL SLAG

The steel industry is growing in Brazil, and the country is among the world's largest producers of Fe, which has generated more than 6.25 million tons of slag each year, which are often accumulated in the yards of steel mills (Pereira et al., 2010; Sobral et al., 2011). The municipality of Parauapebas (PA) is located in the largest mineral province in the world (Serra dos Carajás), notably with regard to Fe extraction. Thus, the residues of the Fe and steel industry, obtained by different processes, are easily found in the steel mills of the region, especially in the municipality of Marabá in the southeast of the state of Pará, where the steel pole is located.

In the production of pig iron in blast furnaces and steel in steel mills, slag is the result of processing at high temperatures (above 1400°C), when the silica present as an impurity in the ferrous ore reacts with the limestone added to it as a flux (Sousa et al., 2010), generating neutralizing constituents based on Ca and Mg (Ca and Mg silicates), in addition to Si itself that can be used as fertilizer. Thus, steel slag is the cheapest and most abundant source of silicates (Stocco et al., 2010), already being used as acidity correctives in the United States and Japan, also showing an increase in the availability of Si and other elements (Pereira et al., 2010). The sustainable use of a by-product of the industry, whose fate would be uncertain, represents a socioeconomic benefit, minimizing the environmental liability generated by the accumulation of slag in steel mills, in addition to promoting regional development.

After mining, cattle ranching comes as the second largest economic activity in the southeast of Pará. However, most animal production is carried out in extensive systems, with the most cultivated grasses, those of the species *Urochloa brizantha*, settled in soils of low fertility (Latosols and Ultisols). Brazil has about 100 million hectares of cultivated pastures, many of which have been grazing for more than 10 years, with 60% in an advanced stage of degradation (Sávio et al., 2011). Slag is an alternative, as the leaf accumulation of Si in grasses attenuates the toxic effects of Al, Mn and Fe, forming a physical barrier for the reduction of transpiration, promoting resistance to pest and disease attack (Faria et al., 2008; Sousa et al., 2010), in addition to providing more upright leaves, increasing photosynthetic efficiency in terms of light capture (Crusciol, 2006), thus avoiding early degradation and ensuring the perpetuity of pastures.

There are some studies that deal with the use of slag only as an acidity corrective and its relationship with the response of grasses, but there are few that report the use of silicates as a source of Si for forage grasses (Stocco et al., 2010). Several studies have shown that grasses respond favorably to silicate fertilization, particularly when cultivated in soils with low levels of available Si (Sousa et al., 2010), although in the tropical region, there is no well-defined information regarding the critical levels of Si in the soil and in the plant (Faria et al., 2008). Even with few experimental results, especially for forage grasses, slags have been used both for acidity correction and for Si supply. In this context, plants can be classified according to their absorption of Si into accumulators, intermediates and non-accumulators. Grasses in general are recognized as accumulators of Si, such as *U. brizantha* (Sávio et al., 2011), and this accumulation strategy should be better studied.

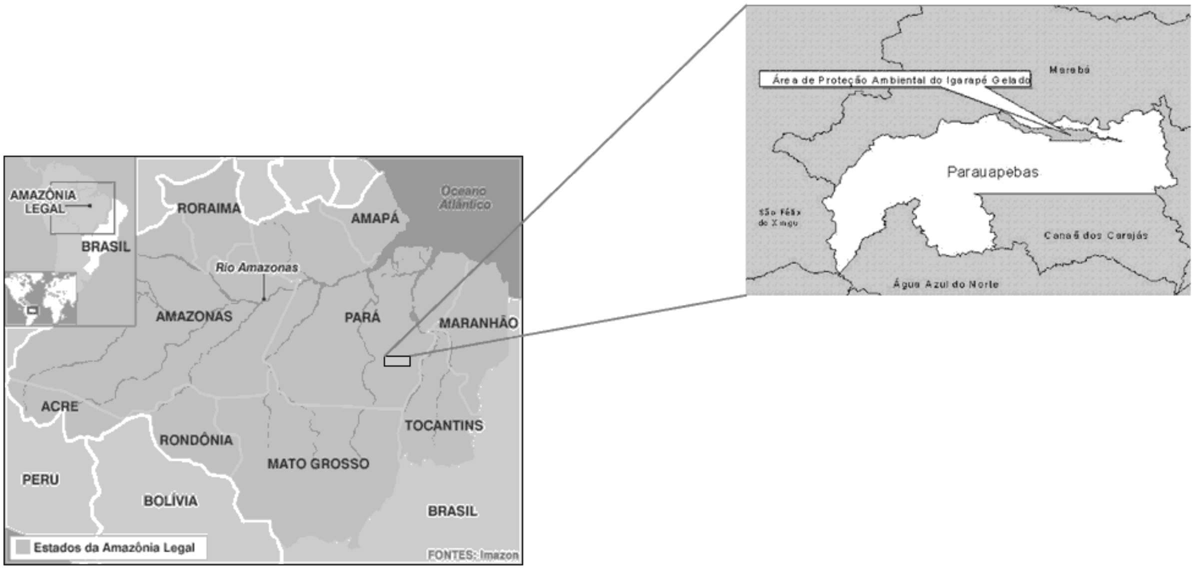
Silica is an amorphous polymer of hydrated silicon dioxide (SiO2.nH2O), occurring in leaf structures in the form of opaline mineral scales called siliceous bodies (Tomlinson, 1961). The presence and structural diversity of silica bodies are well documented in different plant families, although the physiological mechanisms that form them are questioned (Silva; Potiguara, 2009). Although the accumulation of silica in grasses is a relatively known phenomenon under natural conditions, without slag fertilization, the quantification of siliceous bodies and the Si contents in trichomes, of the aerial parts of forage grasses, due to the greater availability of Si in the soil, is not known, especially when it comes *to U. brizantha* cv. Xaraés. Trichomes participate in numerous plant physiological mechanisms (Potiguara et al., 2013), and the degree of participation in the strategy of Si accumulation in leaf tissues should be investigated. This information may help to explain the relationship between biogenic silica in plants and its functions in plants.

The present study aimed to evaluate the effects of the application of blast furnace steel slag on the amount of siliceous bodies and on the Si content of the trichomes of the leaf blade of *Urochloa brizantha* cv. Xaraés, aiming to contribute to the identification of strategies for accumulation of Si via foliar.

Methodology

The work was carried out on a rural property, with dairy farming activity of producers settled in the Igarapé Gelado Environmental Protection Area – APA, with 21,600 ha and a perimeter of 141.8 km (Figure 4). The experimental area was located in the southeast of the state of Pará, at the intersection of the Igarapé Gelado and the Carajás Railroad – EFC, with geographic coordinates equal to latitude 06º 00' 10" S and longitude 49º 57' 43" W, 30 km away from the municipality of Parauapebas (PA).

Figure 4. Location of the Igarapé Gelado Environmental Protection Area.



Source: Imazon (2011).

The place is classified as an Amazon Forest zone, with average rainfall around 1,700 to 2,000 mm $^{year-1}$, which concentrates between November and April (70%). Average annual temperatures are high and generally higher than 23ºC. Average relative humidity is approximately 70% in the driest months. The relief is classified at 8% as flat to smooth wavy. The experiment was conducted in Ultisol (EMBRAPA, 2013), which presented fertility, at a depth of 0 - 0.20 m, equal to: pH (H2O) = 5.40; P (Mehlich-1) = 3.58 mg dm-3; Na =

5.95 mmolc dm-3; K+ (Mehlich-1) = 93.00 mmolc dm-3; Ca2+ (KCl 1 mol $^{L-1}$) = 21.67 mmolc dm-3; Mg+2 (KCl 1 mol $^{L-1}$) = 7.83 mmolc dm-3; H+Al (Ca(OAc)2 0.5 mol $^{L-1}$) = 35.08 mmolc dm-3; sum of exchangeable bases (SB) = 128.45 mmolc $^{dm-3}$; Total CEC = 163.53 mmolc dm-3 and base saturation (V%) = 78.55%.

The experimental design was randomized blocks with four replications. The plots, 6 m wide and 8 m long, were constituted by the following treatments: 1- no slag application; 2- 200 kg of slag $^{ha-1}$; 3- 400 kg $^{ha-1}$ and 4- 600 kg $^{ha-1}$. Blast furnace slag was selected to be used as silicate fertilizer in the present experiment due to its greater availability and chemical characteristics, such as 41% SiO2, 26% CaO and 4% MgO. The blast furnace slag was passed through a sieve with a 2.0 mm mesh (ABNT nº.10) to achieve a particle size similar to that of commercial correctives and fertilizers.

Sieved samples of blast furnace slag were packaged and sent to the Fertilizer and Corrective Laboratory of the Faculty of Agrarian Sciences of UNESP / Botucatu (SP) for the determination of moisture content (5.40%), reactivity - RE (67.53%), neutralization power - PN (50.00%) and relative total neutralization power - PRNT (34.00%). Then, the sample collected from the blast furnace slag was sent to the Laboratory of Scanning Electron Microscopy of the Emílio Goeldi Museum of Pará, to obtain electromicrographs and perform microanalyses by Energy Dispersive Spectroscopy (EDS).

The application of the slag occurred manually and in cover over the soil, at the beginning of the rainy season, after the lowering of the pasture, by controlled grazing with dairy cows, until reaching the ideal height for *U. brizantha*, which was between 0.25 and 0.35 m. After the application of the treatments (slag doses), for a period of 3 months (in the middle of the rainy season), The area was closed to the access of cattle until the pasture was close to the optimal cut-off point, coinciding with the production of dry matter and nutritive value. At this stage, prior to the beginning of flowering, the effect of silicate fertilization was effectively evaluated, so that there was a new lowering of the pasture.

The analyses were carried out with young and adult leaves (n=5) collected from the median region of the clumps of *U. brizantha* cv. Xaraés of the plots without slag and with a maximum dose of 600 kg of slag $^{ha-1}$. Samples were fixed in FAA70 (PA formaldehyde, PA acetic acid and 70% ethyl alcohol, 1:1:18, v/v) for 24 hours (Johansen, 1940), washed and preserved in 70% ethyl alcohol (Potiguara et al., 2013), for subsequent observation in a scanning electron microscope (SEM).

For SEM analysis and energy dispersive spectroscopy (EDS), leaf samples dehydrated by the Johansen (1940) increasing ethyl series were dried in a CO2 critical point apparatus, adhered to metal supports by double-sided carbon tape and metallized with a gold layer of approximately 20 nm thick for 150 seconds in a 25 mA current (Potiguara et al., 2013). Electromicrographs were obtained using a LEO 1450 VP scanning electron microscope, using secondary electron (ES) and backscattered electron (ERE) detectors, with electron acceleration and working distance of 15 Kev and 15 mm, respectively. The micrometric scales were obtained at the same time as the electromicrograph capture and projected under the same optical conditions.

Chemical analyses by EDS were performed to determine the silicon content in trichomes and leaf siliceous bodies, as was done for blast furnace steel slag, in determining its elemental chemical composition. For this purpose, a Gresham X-ray detector, model Sirius 10/7.5 coupled to the SEM, was used, operated under the same conditions as the electromicrographs (Potiguara et al., 2013).

To count the siliceous bodies, 10 leaf blade fields of 0.021 mm2 were used, considering the adaxial and abaxial surfaces for the regions of the central vein, margin and semilimbus of the leaf apex, middle and base, totaling 60 observational fields per region and 180 per leaf blade. Quantification was done on the SEM Leo model 1450 VP itself, at a 695X increase established as standard.

The results of the leaf structural modifications related to the application of steel slag are presented in the form of scanning electromicrographs with respective spectra of the in situ EDS analysis and clustered column type graphs, with the mean percentage values of the Si contents and the respective ± standard errors.

The determination of the dry matter (M.S.) produced by the pasture was carried out close to the optimal cut-off point, coinciding with M.S. production and nutritive value. At this stage, prior to the beginning of flowering, the green matter was cut above 0.25 m from the ground. The material was separated into leaf and stem, dried in a forced air circulation oven, about 65°C.

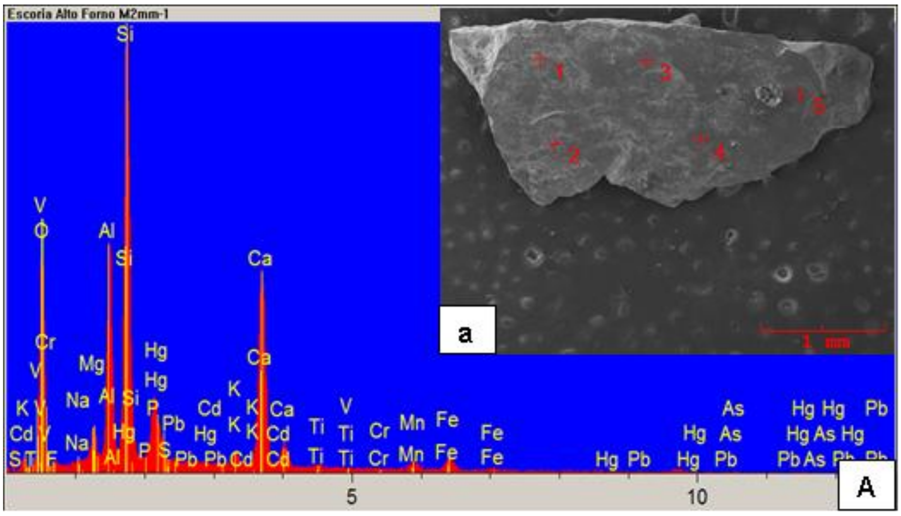
Results and Discussion

The answers to the use of steel slag in pastures as a soil corrective are being widely studied. However, the purpose of the present work was to use blast furnace slag as a source of Si and not as an acidity corrective material. In this sense, as the desired V% for *U. brizantha* was between 50 and 60 (Raij et al., 1997) and the V% of the soil, at the time of slag application, was 78%, it can be stated that any quantitative or qualitative modifications in the leaf blades were exclusively due to the action of Si inside the plants.

In general, the sources of Si in the form of silicate bonded to a cation have been those with the highest solubility and availability of Si to plants (Pereira et al., 2010), as is the case of blast furnace slag. Also, the rainy season in the three months after the application of the slag on the soil favored the solubilization of the material and the absorption of Si by the plants. Thus, blast furnace steel slag has the potential to be used in agriculture, not only as a supplier of Ca and Mg or only as a corrective material for soil acidity, but also as a source of Si to cultivated vegetables.

Figure 5 highlights that, with the spectroscopic microanalyses of X-rays by energy dispersion (EDS) and obtaining electromicrographs, the highest absorbance peaks were for the Si, where the absorbance is directly proportional to the concentration. This characterizes this material as having high potential for use as a silicate fertilizer. Also, a high concentration of heavy metals or other harmful elements was not detected, and there is no danger of environmental contamination by blast furnace slag applied to the soil.

Figure 5. Spectrum of EDS analysis (A) with the respective scanning electromicrograph (a) of blast furnace slag.



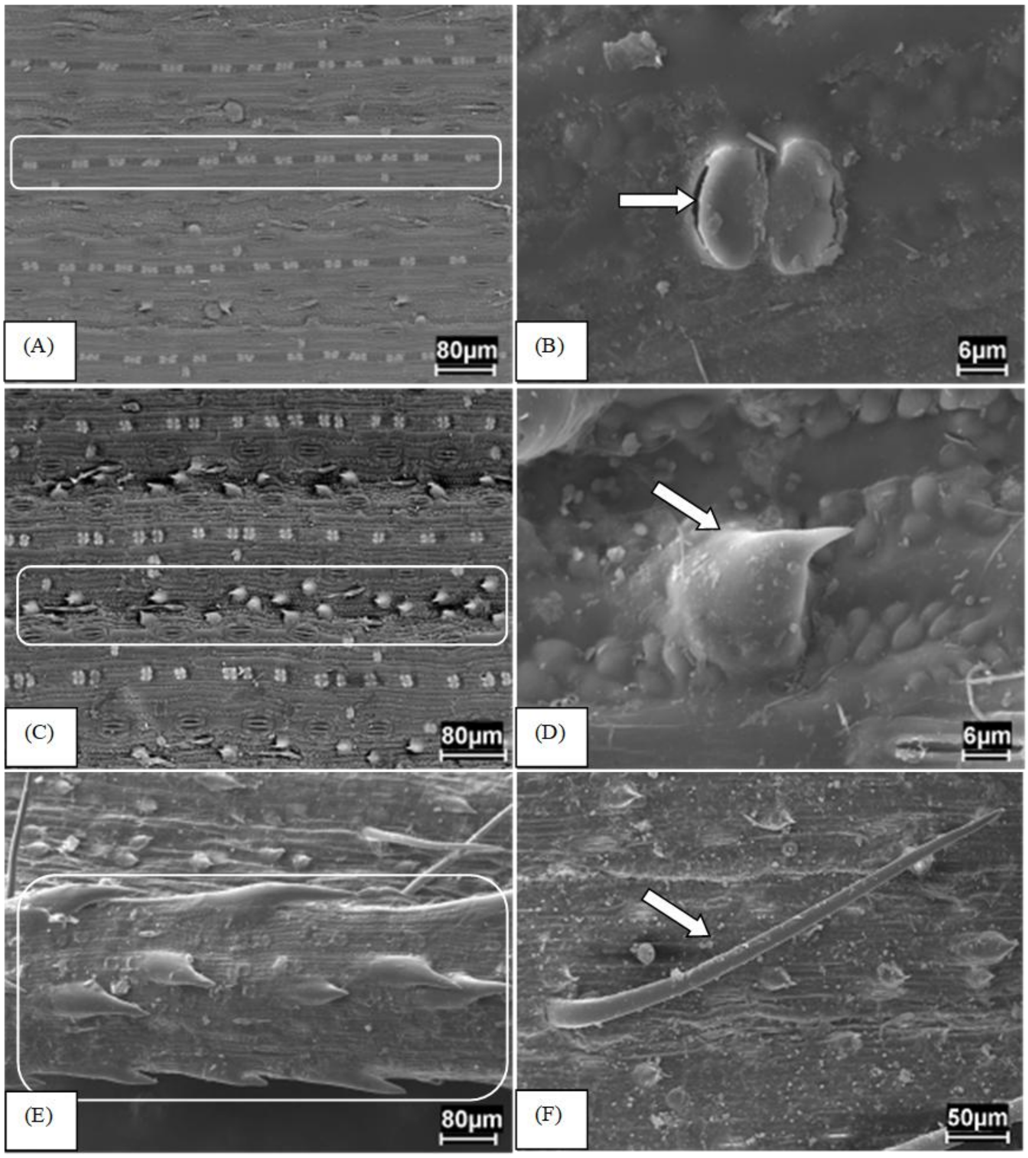
Source: Prepared by the authors based on the original results of the research.

Although it is not considered an essential element for plants, Si tends to accumulate in the leaf blades (Braga et al., 2009), young and adult, more specifically inside the epidermal cells, regardless of the application or not of slag in the soil. With or without the application of slag, it is possible to identify the formation of siliceous bodies (SC), organized in parallel rows along the axis of the leaf (Figure 6A). These CS are shown as dumbbell-shaped siliceous particles (Figure 6B), located on the surface of the leaf blade of *U. brizantha*, as also characterized by Potiguara et al. (2013), being an ergastic substance characteristic of the leaf micromorphology of grasses (Metcalfe, 1960).

Therefore, dumbbell-shaped SCs are typical of grasses and are the main form of deposition and accumulation of Si (Silva; Alquini, 2003), thus being a strategy recognized and adopted by *U. brizantha* to accumulate the excess of Si that was available in the soil and was absorbed by the plant. The question is to know if after reaching the genetic limit of

Si deposition in the form of CS, with the high availability of this element in the soil by silicate fertilization with blast furnace slag, the forage grass used in this experiment would present an additional strategy to be able to accumulate even more silicon.

Figure 6. Scanning electromicrographs of the leaf blade surface of *Urochloa brizantha* cv. Xaraés. (A): General view of the abaxial face by ERE, highlighting the organization of the siliceous bodies in dumbbells (demarcated by a rectangle). (B): Detail by ES of a dumbbell body of the adaxial face (indicated by an arrow). (C): General view of the abaxial face by ERE, highlighting the trichomes tectores aculeiformes (demarcated by a rectangle). (D): Detail by ES of an aculeiform trichome of the adaxial surface (indicated by an arrow). (E): Detail by ES of marginal aculeiform trichomes (demarcated by a rectangle). (F): Detail by ES of a cordiform tector trichome of the abaxial face (indicated by an arrow). (B, C and D) = young leaves. (A, E and F) = adult leaves. (A, C and D) = plants not fertilized with slag. (B, E and F) = plants fertilized with slag).



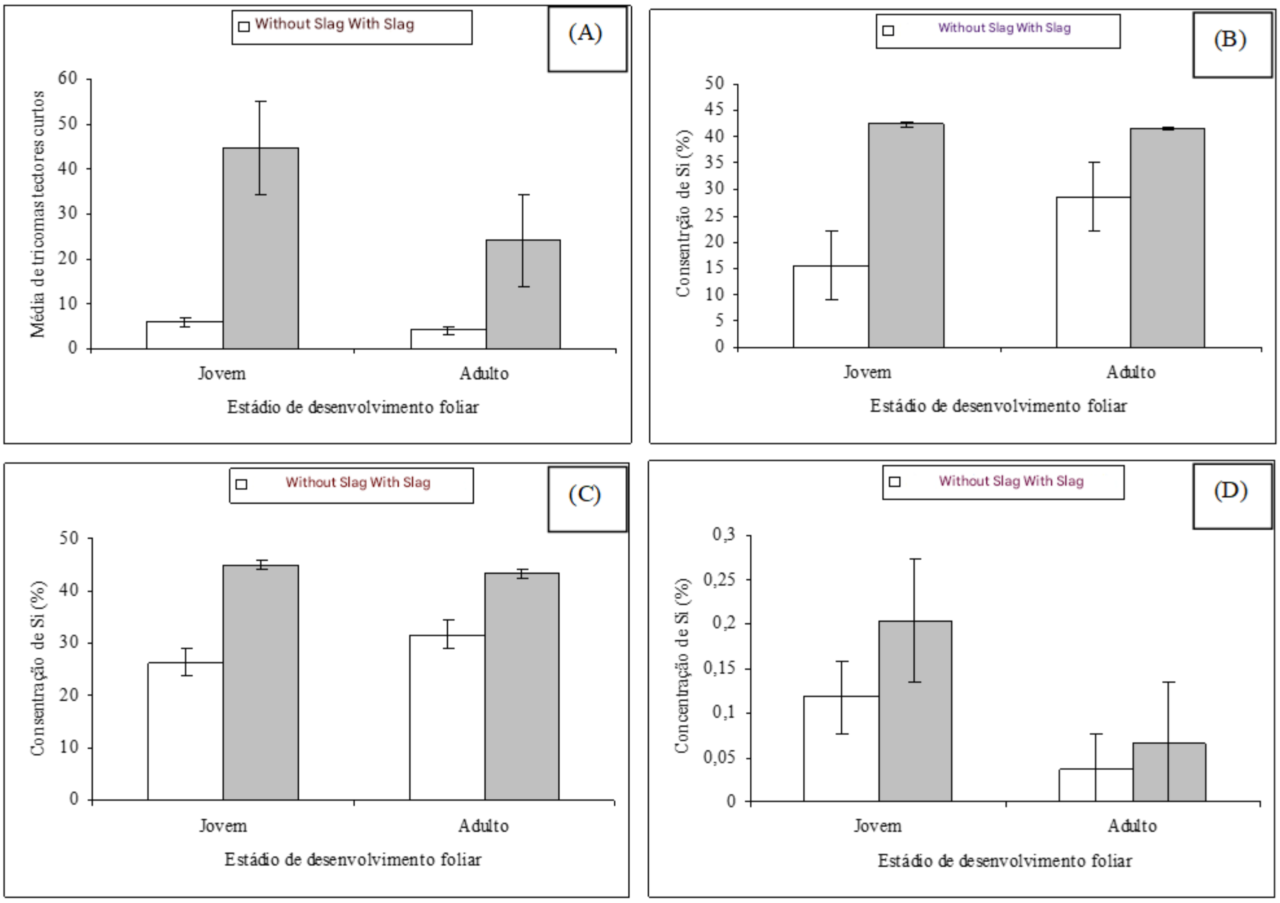
Source: Prepared by the authors based on the original results of the research.

It was clear that if Si is available, absorbed by plants in greater quantity, especially in soil fertilized with slag such as the one in the present work, it is metabolized into mineral biocompost and accumulated in the form of CS, perhaps due to the absence of a specialized excretory system (Haberlandt, 1925). However, the occurrence of SC and the morphology of these mineral scales are genetically determined and little influenced by environmental factors (Moller; Rassmussen, 1984). Thus, there is a limit to the deposit of Si in the form of CS (opal) (Metcalfe, 1983). Biogenic silica in plants may be related to leaf reflectance, mechanical protection against insect and pathogen attack, control of excessive transpiration and water retention, prevention of underlying tissue collapse under drought conditions, and the balance of thermal exchanges with the external environment (Silva; Potiguara, 2009). In addition, the Si accumulated in the leaf allows it to become more upright, increasing the leaf area exposed to sunlight, improving its photosynthetic efficiency (Crusciol, 2006).

By anatomical analysis of the young and adult leaves of *U. brizantha* cv. Xaraés, it was also possible to demonstrate the presence of other Si deposits that occur in the form of aculeiform tector trichomes (TA) (Figure 6C, D and E) and filiform tector trichomes (TF) (Figure 6F). These Si deposits are usually located close to the epidermis, in the form of appendages, and may occur in the cell wall (Braga et al., 2009). It is also observed that the AT are distributed over the entire surface of the leaves, more specifically between the parallel rows of the SC (Figure 6C), both on the abaxial and adaxial faces (Figure 6D) and in a restricted way on the margin of the leaves (Figure 6E). On the other hand, the TF, in smaller quantities, is randomly distributed throughout the leaf limb (Figure 6F).

Figure 7A shows that, regardless of the leaf development stage (young or adult), the application of 600 kg of slag $^{ha-1}$ provided an increase in the amount of TA, indicating greater accumulation of Si. Figures 7B and C corroborate the previous fact, showing that the concentrations of Si (%) naturally increased in the TA as a function of the application of the maximum dose of slag (600 kg $^{ha-1}$). This increase was also observed for ET (Figure 7D), regardless of whether the leaf was young or adult.

Figure 7. (A): Mean siliceous bodies in plants of *U. brizantha* cv. Xaraés. (B – D): Si concentration (%) of tector trichomes. (B and C): aculeiform trichomes, being (C) specific to those of the margin and (D): filiform trichomes. For treatments with and without maximum slag dose, depending on the stage of leaf development.

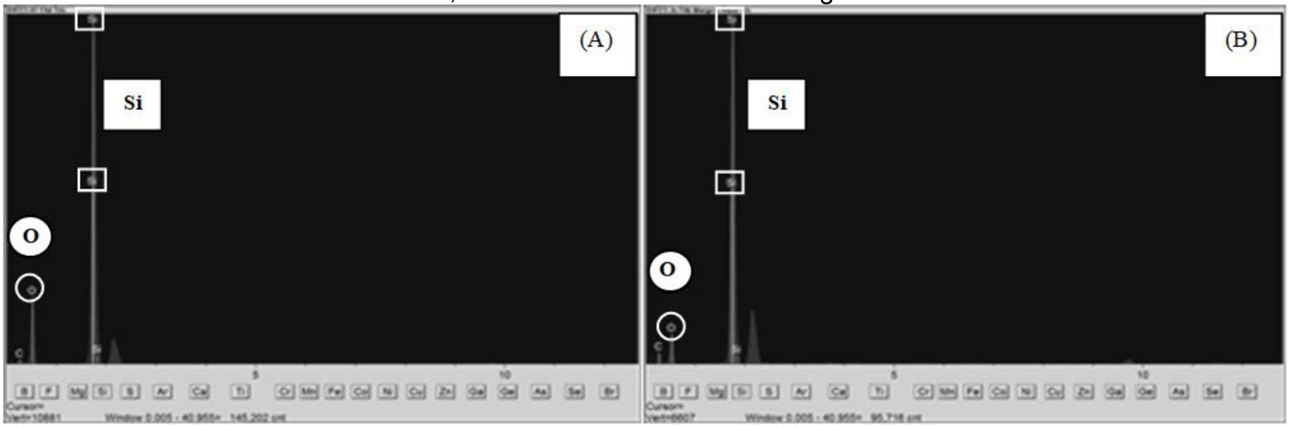


Note: Values are averaged ± standard errors.
Source: Prepared by the authors based on the original results of the research.

For the TA of the leaf margin (Figure 7C), the very pronounced accumulation of Si in the plots that received slag treatment (600 kg $^{ha-1}$), explains the fact that the leaves of *U. brizantha* cv. Xaraés presented margins with a purplish color and much more cutting than the margins of the leaves of plots without slag treatment, where the purplish color was not verified in the field observations. The "droplet" structure of the AT (Figure 6D), whose pointed parts of silica are projected to the outside of the epidermis, at the leaf margins, is noteworthy (Figure 6E). These pointed appendages that are grouped in sequence, around the margin of the leaf blade, all facing the leaf apex, forming the recognized cutting surface of the leaves of grasses.

In Figure 8, through the spectrum of the EDS analysis of the TA of the margins of young and adult leaves, which received slag fertilization, it is possible to verify the highest absorbance peaks for Si, which correspond to the high average concentrations of this element shown in Figure 7C. Figure 8, with the spectrum of the EDS analysis performed in the TA, it was also possible to detect peaks of O, indicating that Si is in the form of dioxide.

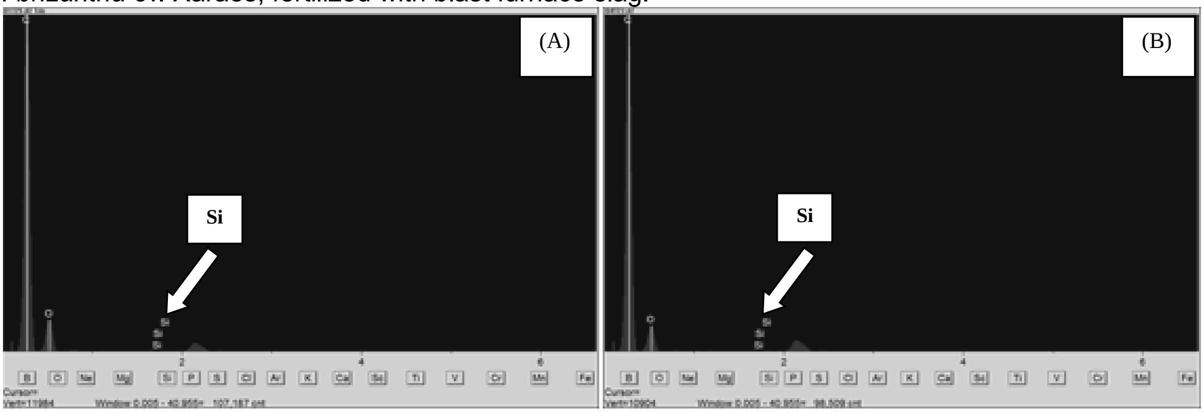
Figure 8. Spectra of EDS analyses performed on aculeiform trichomes from the margin of (A) young and (B) adult leaves of *U. brizantha* cv. Xaraés, fertilized with blast furnace slag.



Source: Prepared by the authors based on the original results of the research.

The finding that in *U. brizantha* cv. Xaraés, the TA accumulate Si, suggests that such structures act as a second strategy or supplementary alternative strategy to absorb, accumulate and, or in a certain way "discard" the surplus of Si that was available in the soil and was absorbed by the plants, since a limit of accumulation performed by the CS was found. Until then, only CS were considered as the main structure of Si deposition and accumulation in grasses. Regarding the low Si contents of TF (Figure 7D), independent of the stage of leaf development and treatment, suggest that this element is acting as a structural component of the wall of these trichomes, indicating that they perform other biological functions in *U. brizantha* cv. Xaraés, not only related to the deposit and accumulation of Si. In Figure 9, spectra of EDS analyses of the filiform tector trichomes of young and adult leaves confirm their inability to accumulate Si in large quantities, even with high availability of the element in the soil.

Figure 9. Spectra of EDS analyses performed on the filiform tector trichomes of (A) young and (B) adult leaves of *U. brizantha* cv. Xaraés, fertilized with blast furnace slag.



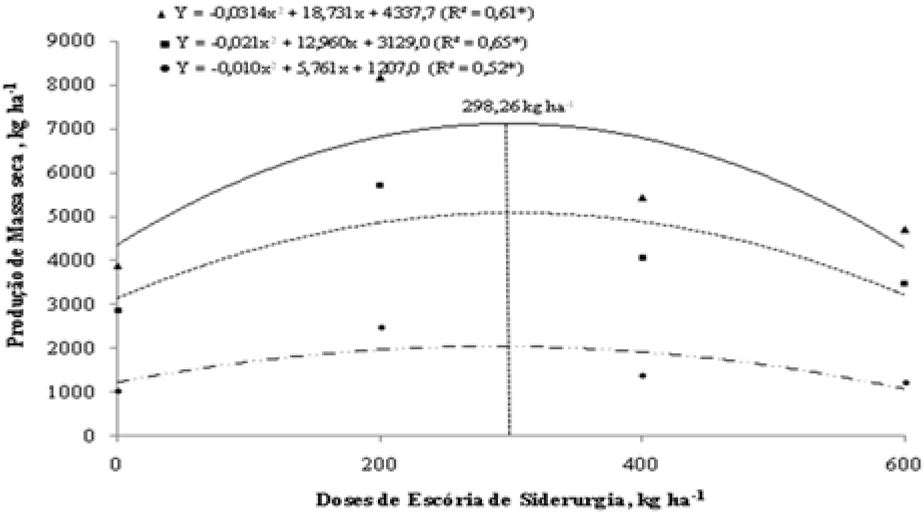
Source: Prepared by the authors based on the original results of the research.

In general, trichomes perform numerous functions for plants, being able to offer physical protection against phytophagous larvae of some insects, disperse aphid colonies, eliminate allelopathic substances that decrease the vigor of seedlings in their vicinity, prevent the entry of chemicals used in agriculture, provide a water-saturated microenvironment between the stomata and the environment, avoiding desiccation, and influencing the direct action of the sun's rays that fall on the leaf blade (Potiguara et al., 2013). In addition to siliceous bodies and trichomes, in the leaf epidermis, Si can also combine with cellulose, can be present in the guard cells of the stomata and can be found in vascular elements (Silva et al., 2005).

The functions of SC and trichomes, regarding the morphological and physiological benefits they can add to plants, have been generalized by several authors, and there is, for example, no clear and objective discernment of who is effectively responsible for increasing photosynthetic efficiency, resistance to pests and diseases and greater tolerance to lack of water, in relation to the two strategies of Si accumulation. However, it is important to emphasize the need to expand research that will elucidate the specific function or the exact participation of SC and the different types of trichomes in the quantitative and qualitative modifications of plants, occurring due to the greater presence of available Si in the soil. In addition, it will also be important to verify whether these structural changes observed in the present work will lead to changes in the primary growth of plants, in the development and, consequently, in the agricultural productivity.

The structural and chemical alterations, of a quantitative nature, verified in the leaf blades of *U. brizantha* cv. Xaraés, provided by the application of steel slag, allow us to suggest further studies in order to verify whether they would cause any change in terms of the increase in the production of dry matter, in the nutritive value of the forage and its palatability to ruminant animals, needing, at least, to determine the bromatological characteristics of the species, with and without the application of slag. Korndörfer et al. (2010) observed that calcium silicate was efficient to increase Si concentrations in *U. brizantha* and *Megathirsus maximus plants*, but did not alter the dry matter production of the species. On the other hand, Lima et al. (2004) found that the application of 700 kg $^{ha-1}$ of blast furnace slag in U*. brizantha pastures* provided an increase in the production of shoot dry matter. In the present experiment, there was an effect of the application of slag ($P<0.05$) on the S.M. of leave, stem and total, showing a quadratic behavior (Figure 10). With the dose of 298.26 kg $^{ha-1,}$ the highest production of M.S. was observed, reaching 7,131.66 kg $^{ha-1}$ of total M.S.

Figure 10. Effect of the application of steel slag doses on the production of dry mass of stem (●), leaf (■) and total (▲) in *Urochloa brizantha* cv Xaraés. * (P<0.05).



FINAL CONSIDERATIONS

Of the three slags studied, due to the silicon content, they can be classified as silicate slag fertilizers, especially blast furnace slag and electric furnace slag, with no concentration of heavy metals or other toxic elements;

The greater availability of Si by the application of blast furnace slag indicated that there is a limit to its deposition in the form of siliceous bodies, with the aculeiform trichomes as an alternative strategy for *Urochloa brizantha to* continue absorbing and accumulating the surplus of Si;

Auto furnace slag can be used in pastures of *Urochloa brizantha* cv. Xaraés, with the dose between 200 and 400 kg $^{ha-1}$, providing the highest production of dry mass.

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