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PHYSICAL CHARACTERISTICS OF SOIL SUBJECTED TO SILICATE AND LIMESTONE APPLICATIONS, WITH YIELD RESPONSES IN CORN AND WHEAT GROWN RED LATOSOL (OXISOL)

CARACTERÍSTICAS FÍSICAS DE SOLO SUBMETIDAS A SILICATO E CALCÁRIO COM RESPOSTAS DE PRODUTIVIDADE NO MILHO E TRIGO EM LATOSSOLO VERMELHO DISTROFÉRRICO

CARACTERÍSTICAS FÍSICAS DEL SUELO SOMETIDO A APLICACIONES DE SILICATO Y CALIZA, CON RESPUESTAS DE RENDIMIENTO EN MAÍZ Y TRIGO CULTIVADOS EN LATOSOL ROJO (OXISOL)

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ABSTRACT

The objective of this study was to evaluate whether treatments with calcium and magnesium silicate and dolomitic limestone improved soil physical properties, increased chlorophyll and carotenoid levels, and enhanced crop productivity. The study was conducted in an experimental area in the municipality of Céu Azul, PR, Brazil, using soybean, wheat, and a corn hybrid cultivars. The experimental design was completely randomized, with 3 treatments and 9 replications, totaling 27 experimental units. Application rates of 0, 300, and 800 kg ha^{-1} were established for the control, silicate, and limestone treatments, respectively. Physical soil samples were collected to determine particle density, bulk density, macroporosity, microporosity, and total porosity. Soil penetration resistance was also evaluated using an impact penetrometer. Additionally, chlorophyll and carotenoid contents were quantified for the soybean cultivar and corn hybrid, and crop yield indices were measured for the wheat and corn crops. The means were analyzed using Tukey's test at a 5% significance level. The treatments did not improve bulk density, macroporosity, microporosity, or total porosity. The degree of soil compaction was higher in the silicate treatment. The variables carotenoids, chlorophyll 'a', chlorophyll 'b', and total chlorophyll did not differ among treatments. The productivity of wheat and corn crops did not differ statistically between treatments.

KEYWORDS: Bulk density. Soil porosity. Soil remineralizer. Penetration resistance.

RESUMO

O trabalho tem por objetivo avaliar se os tratamentos de silicato de cálcio e magnésio e calcário dolomítico proporcionaram melhorias nas propriedades físicas do solo, aumento nos índices de clorofila, carotenoides e produtividade agrícola. O trabalho foi conduzido em uma área experimental no município de Céu Azul, PR, com cultivares de soja, trigo e híbrido de milho. O delineamento utilizado foi o inteiramente casualizado, com 3 tratamentos e 9 repetições, totalizando 27 unidades experimentais. Foram definidas as dosagens de 0, 300 e 800 kg ha^{-1} para os tratamentos

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testemunha, silicato e calcário, respectivamente. Foram coletadas amostras físicas de solo, para a determinação de densidade de partícula e aparente, macroporosidade, microporosidade e porosidade total. Também avaliou-se a resistência à penetração dos solos, com um penetrômetro de impacto. Realizou-se ainda a quantificação dos teores de clorofilas e carotenóides para a cultivar de soja e híbrido de milho, bem como a verificação dos índices de produtividade para as culturas de trigo e milho. As médias foram submetidas ao teste de Tukey com 5% de significância. Os tratamentos não proporcionaram melhorias na densidade aparente, macroporosidade, microporosidade e porosidade total. O grau de compactação foi maior no tratamento com silicato. As variáveis carotenóides, clorofila 'a', clorofila 'b' e clorofila total não apresentaram diferenças entre os tratamentos. A produtividade das culturas de trigo e milho não diferiram estatisticamente para cada tratamento.

PALAVRAS-CHAVE: Densidade e porosidade de solo. Remineralizador de solo. Resistência à penetração.

RESUMEN
El objetivo de este trabajo fue evaluar si los tratamientos con silicato de calcio y magnesio y cal dolomítica mejoraron las propiedades físicas del suelo, incrementaron los índices de clorofila, carotenoides y la productividad agrícola. El estudio se llevó a cabo en un área experimental en el municipio de Céu Azul, PR, utilizando cultivares de soja, trigo y un híbrido de maíz. El diseño experimental empleado fue completamente al azar, con 3 tratamientos y 9 repeticiones, totalizando 27 unidades experimentales. Se definieron dosis de 0, 300 y 800 kg ha^{-1} para los tratamientos testigo, silicato y cal, respectivamente. Se recolectaron muestras físicas de suelo para determinar la densidad de partículas y la densidad aparente, así como la macroporosidad, microporosidad y porosidad total. También se evaluó la resistencia a la penetración del suelo utilizando un penetrómetro de impacto. Además, se cuantificaron los contenidos de clorofilas y carotenoides para la cultivar de soja y el híbrido de maíz, así como los índices de productividad para las culturas de trigo y maíz. Los promedios fueron sometidos a la prueba de Tukey con un nivel de significancia del 5%. Los tratamientos no mejoraron la densidad aparente, la macroporosidad, la microporosidad ni la porosidad total. El grado de compactación fue mayor en el tratamiento con silicato. Las variables carotenoides, clorofila 'a', clorofila 'b' y clorofila total no presentaron diferencias entre los tratamientos. La productividad de las culturas de trigo y maíz no difirió estadísticamente entre los tratamientos.

PALABRAS CLAVE: Densidad aparente. Porosidad del suelo. Remineralizador del suelo. Resistencia a la penetración.

INTRODUCTION

The growing demand for food has intensified the need to increase crop yield, which requires increasingly efficient and sustainable production systems. In this context, proper soil management and plant nutrition become key factors in ensuring adequate crop development, from establishment through grain formation and harvest. For this process to occur efficiently, it is essential to adopt agronomic practices that reconcile productivity, soil conservation, and plant nutritional balance.

Among the aspects that directly influence agricultural performance, soil structural quality and its capacity to supply nutrients to plants are particularly relevant. Degraded, compacted, or highly acidic soils can limit root growth and reduce the availability of essential nutrients, compromising crop development. In addition, soil acidification favors the presence of elements such as iron and

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aluminum that can immobilize important nutrients, such as phosphorus, reducing their availability to plants. Thus, soil correction and management strategies are essential to maintain its functionality and ensure the sustainability of production systems.

In this scenario, the use of soil amendments and conditioners has been widely adopted in agriculture, especially those that provide calcium, magnesium, and silicon. Calcium plays an essential role in plant growth and development, participating in the formation and stability of the cell wall, in addition to acting in physiological processes related to metabolic regulation, cell signaling, and maintenance of tissue structural integrity. The adequate presence of this nutrient contributes to the proper functioning of processes such as respiration, photosynthetic activity, and plant response to different stress conditions.

At the same time, silicon has been highlighted in agronomic studies due to its beneficial effects on both soil and plants. In the soil, this element can interact with other minerals, influencing nutrient dynamics and contributing to improvements in physical properties, such as structure and reduction of compaction processes. In agricultural systems where soil amendments are frequently applied and machinery traffic is intense, such improvements are particularly important for promoting root development and efficient use of available resources.

In plants, silicon can act to strengthen cell structures, forming a protective layer in plant tissues that increases resistance to pathogens and insect pests. In addition, this element is associated with improvements in water and nutrient absorption, root growth, and the physiological efficiency of plants. Studies also indicate that its presence can contribute to increased photosynthetic activity, maintenance of chlorophyll levels, and greater nutritional balance, factors that directly affect crop growth and productivity (Zhang et al., 2019; Malik et al., 2021). Another relevant aspect is its role in mitigating biotic and abiotic stresses, such as salinity, water deficit, and oxidative stress (Nisar et al., 2022; Nazim et al., 2024).

Given this context, it is important to evaluate alternatives that can simultaneously contribute to improving soil properties and plant physiological performance. Thus, this study aimed to evaluate whether the application of calcium and magnesium silicate, compared to the use of dolomitic limestone, promotes improvements in soil physical properties, as well as to verify its effects on chlorophyll, carotenoid, and crop yield indices.

MATERIAL AND METHODS

Characterization of the experimental area

The experiment was set up on a commercial property with an area of 15 hectares (Figure 1) in the municipality of Céu Azul, Paraná, in the western region of the state. It was developed during the winter and summer agricultural seasons throughout the years 2020, 2021, 2022, 2023, and 2024,

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in wheat, second-season corns, and soybeans. The local altitude is 663 meters, and the central geographic coordinates are 25°7'5.75" S 53°49'18.61" W. The region's climate, classified by Köppen, is type Cfa, humid subtropical, with average annual temperatures ranging from 19.5 to 20.1 °C, with low incidence of frost and total annual rainfall ranging from 1550 to 1650 mm year^{-1}(Köppen, 2019).

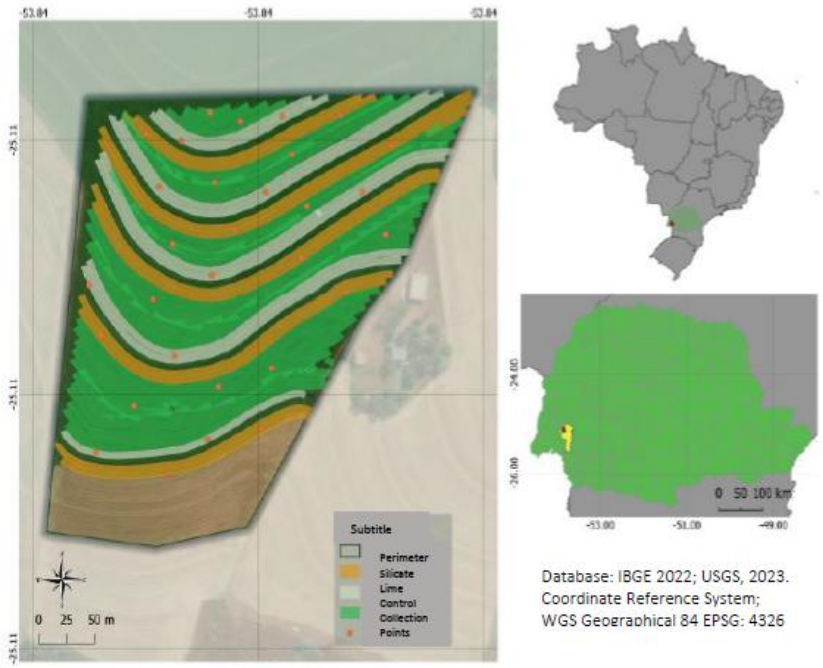


Figure 1. Commercial agricultural experimental area, located in the municipality of Céu Azul, PR.

Thirty sampling points were randomly demarcated with uniform distribution using the QGIS 3.4 software. Subsequently, physical and chemical soil samples were collected to characterize soil texture in the 0–0.20 m layer (Table 1). The samples were sent to the Federal Technological University of Paraná (UTFPR), Pato Branco campus, Paraná. Based on these analyses, the soil (Table 1) was classified as a typical Dystroferric Red Latosol (Oxisol) with a clayey texture (EMBRAPA, 2018).

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Table 1. Analysis of soil texture in the experimental area carried out at three points in the 0–0.20 m layer on December 4, 2020

Treatments	Texture		
	Sand	clay	silt
	----------	g kg^{-1}	----------
Control	52.0	780.0	168
Silicate	42	800.0	157
Limestone	63.0	800.0	137
Average	52.3	793.3	154

After obtaining the soil texture results and observing the soil chemical analysis values, three treatments were installed in the experimental area: control, calcium and magnesium silicate, and dolomitic limestone. Then, application rates of 0, 300, and 800 kg ha^{-1} were established for each, respectively. The experiment was conducted in a completely randomized design. Random distribution was performed with 30 sampling points, with 11 points allocated to the control treatment, 9 points to the silicate treatment, and 10 points to the limestone treatment. However, due to statistical calculations, two points from the control treatment and one point from the limestone treatment were discarded, so only 9 points were used for each of the treatments.

A completely randomized design was adopted because the fertilization management of the experimental area, as carried out by the farmer, was homogeneous throughout, as confirmed by previous experiments conducted in the same area.

Both treatments were applied to the surface of the strips by broadcasting, with the aid of a Hercules 7000 Stara distributor. The chemical composition of the soil amendment dolomitic limestone is 25% calcium and 17% magnesium, while silicate contains 9% silicon oxide ($SiO_{(2)}$), 9% calcium (Ca), and 2% magnesium (Mg).

PHYSICAL CHARACTERISTICS OF SOIL

Undisturbed soil samples were collected at 27 points in the area to determine particle density, total porosity, macroporosity, and microporosity. At each collection point, the organic surface layer was removed, and then the numbered stainless-steel cylinder was placed with the beveled end facing down into the soil. The drive head was fitted to the upper base of the cylinder to then drive it into the ground and preserve the physical properties.

Finally, a soil hammer was used to extract the cylinder from the soil profile. The samples were sent to the Soil Physics Laboratory at the State University of Western Paraná for analysis.

In the laboratory, the cylinders were cleaned and placed in a water-filled tray at three-quarters of their height for saturation over 24 hours. At the end of this period, the samples were

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weighed and transferred to a sand column at 60 cm of water tension, where they remained for 48 hours to allow water held in the larger pores to drain by negative pressure through capillary contact between the sample and the sand. Finally, the samples were weighed on a precision balance, and macroporosity was calculated (Equation 1).

Macroporosity = Total porosity – microporosity

Equation (1)

After the process described above, the samples were placed in an oven at 105°C for 48 hours. Upon removal, the samples were weighed to determine the volume of smaller pores (Equation 2), as microporosity is defined by capillary pores, where soil water is retained.

Microporosity = ((MSU - MSS) / MSS) * 100

Equation (2)

Where:
MSU - Wet Soil Mass;
DSM - Dry Soil Mass.

The particle density (Dp) (Equation 3) was also determined using the method of Teixeira *et al.,* (2017). With the aid of a 50 mL volumetric flask containing deionized and deaerated water, a mass of 20 g of soil was measured into a container and oven-dried at 105 °C until a constant mass was achieved. The sample was then transferred to a 50 mL flask, and ethyl alcohol was added until it was completely covered. Subsequently, the flask was shaken to prevent the formation of air bubbles. Finally, the volume of alcohol used was recorded.

$$Dp = \frac{ma}{(Vt - Vu)}$$

Equation (3)

Therefore,
Dp - Particle density, measured in kg dm^{-3} ;
ma - mass of the dry sample at a temperature of 105 °C, in g;
Vt - total measured volume of the flask, in ml;
Vu - volume used to fill the flask with the sample, in ml.

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Finally, the total porosity (Pt) was calculated, which is defined as the ratio between soil density and particle density (Equation 4), according to the methodology of Teixeira *et al.,* (2017).

$$Pt = \left(1 - \frac{Ds}{Dp}\right) \times 100$$

Equation 4

Where

Pt - Total Porosity, in %;

Dp - Particle density, measured in kg dm^{-3};

Ds - Bulk soil density, in kg dm^{-3}.

EVALUATION OF SOIL COMPACTION DEGREE

The degree of soil compaction was assessed using an impact penetrometer, measuring soil resistance to penetration at a depth of 0.60 m. The methodology of Seixas and Souza (2007) was applied, whereby the number of penetrometer impacts is converted to kPa (Equation 5).

$$R = 560 + 689N$$

Equation 5

Where

R - Soil resistance using the penetrometer with penetration in kPa;

N - Number of impacts per decimeter.

SOWING OF WINTER AND SUMMER CROPS

In the winter harvest of 2022, the ORS 1403 wheat cultivar was sown, with fertilization of 390 kg ha^{-1} of the formulated input NPK (nitrogen, phosphorus, and potassium) 10-15-15, with a row spacing of 0.17 m and a depth of 0.04 m. Crop management followed commercial recommendations, comprising three fungicide and two insecticide applications. The interval between applications varied according to weather conditions and pest and disease incidence.

For the 2022/2023 summer harvest, the Brasmax Zeus IPRO soybean cultivar was used, with fertilization of 124 kg $ha^{-1}$of MAP (monoammonium phosphate) with a formulation of 10 52 00 and 103.3 kg ha^{-1} of KCl (potassium chloride), with row spacing of 0.7 m and sowing depth of 0.04 m, at a seeding rate of 18 seeds per linear meter. Crop management followed commercial recommendations, comprising three fungicide and three insecticide applications.

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The second-season corn of 2023 was sown with the Ag 9000 hybrid and fertilized with 413 kg ha^{-1} of NPK 10-15-15 and 165 kg ha^{-1} of urea, at 0.7 m row spacing and 0.04 m depth, at a seeding rate of 4.8 seeds per linear meter. Crop management followed commercial recommendations, comprising three insecticide and three fungicide applications, with intervals adjusted according to weather conditions and pest pressure.

CHLOROPHYLL AND CAROTENOID CONCENTRATION

Leaves were collected to verify chlorophyll and carotenoid concentrations during the flowering stage of the crops. For the soybean cultivars, collections were made in December 2020 and 2022, respectively. However, for the second-season corn, the collection took place in June 2023. The samples were collected at 27 sampling points, with 9 replicates for calcium silicate, 9 replicates for limestone, and 9 replicates for the control. Climatological data were obtained from Simepar, more precisely from the meteorological station in the municipality of Cascavel, Paraná, the closest base to the municipality of Céu Azul. Both municipalities have a humid subtropical climate (Cfa).

To determine chlorophyll and carotenoid levels, the methodology of Arnon (1949), adapted by Viecelli *et al.,* (2010), was used, in which 0.1 g of plant tissue was weighed on a precision balance (1 mg). Immediately afterwards, the chlorophyll a, b, total chlorophyll, and carotenoid (mg g^{-1}) contents of the plant leaves were quantified. The plant tissue samples were stored in a 10 mL glass bottle containing 80% acetone for a period of seven days. At the end of the process, readings were taken in a spectrophotometer at 663, 645, and 450 nm for chlorophyll a, b (Equation 6) and carotenoids (Equation 7), respectively, using the law of Lambert (1870) and Beer (1852), a methodology described by Xavier *et al.,* (2012):

$$Ca = (0.0127 * A_{663}) - (0.00269 * A_{645})$$
$$b = (0.0229 * A_{645}) - (0.00468 * A_{663})$$
$$CT = Ca + Cb$$

Equation (6)

Where:

Ca - chlorophyll a concentration (mg g-1);

Cb - chlorophyll b concentration (mg g-1);

A_{663} - absorbance of the sample at a wavelength of 663 nm;

A_{645} - absorbance of the sample at a wavelength of 645 nm;

CT - total chlorophyll concentration (mg g-1).

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$$C = \frac{A\ x\ 10^4}{E^{1\%}_{1cm}}$$

Equation (7)

Therefore,

C (mg g-1) - Total carotenoid concentration (expressed as carotene);

A - Absorbance of the extract at a wavelength of 450 nm;

$E^{1\%}{}_{1cm}$- Absorbance coefficient of carotene, which corresponds to 2592.

GRAIN YIELD

To evaluate wheat yield, the methodology of Teixeira et al. (2010) was used, where three five-meter rows were manually collected at each point during the physiological maturity phase of the ORS 1403 cultivar. The plants were then placed in paper bags and transported to the Paraná State Rural Development Institute (IDR), where the grains were threshed using a Wintersteiger motorized harvester. Finally, the grain mass content was verified using a digital scale, and the grain moisture content was corrected to 13%.

For corn yield, the manual harvesting method described by Teixeira *et al.,* (2010) was also used. Nevertheless, threshing was performed using a Botini manual thresher.

STATISTICAL ANALYSIS

The collected data were submitted to analysis of variance (ANOVA), applying Tukey's test to identify differences between treatment means at a 5% significance level ($p < 0.05$), using SISVAR (Ferreira, 2010), in a completely randomized design (CRD).

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES OF SOIL

Table 2 presents the mean values of soil physical properties for the 2022/2023 season. The physical properties of the soil were evaluated for the control, limestone, and silicate treatments; the parameters of bulk density, macroporosity, microporosity, and total porosity showed no significant differences, according to Tukey's test at 5% probability. The physical properties of soil mentioned above are in line with those cited by Kiehl (1979), who reports that the ideal conditions for very clayey soil are: bulk density of 0.9 to 1.25 g cm^{-3}, macroporosity above 10%, and total porosity of 50 to 55%. In contrast, the results obtained in the experiment by Castro *et al.,* (2017) report that macroporosity

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was at least 1% higher in latosols corrected with silicate and lime. Nevertheless, the values also did not differ significantly when compared to the control treatment.

Table 2. Results of the physical analysis of soil extracted in the 2022/2023 harvest in soybean cultivation

Treatment	SD	MACRO	MICRO	TP	RP (0-20)	PR (20-40)
	g cm^{-3}	%	%	%	MPa	MPa
Control	1.22a	14.22a	37.30a	51.52a	1.91a	1.64a
Silicate	1.22a	14.83a	36.59a	51.42a	2.07a	1.71a
Limestone	1.25a	12.20a	38.10a	50.30a	1.77a	1.56a
Average	1.23	13.75	37.33	51.08	1.92	1.64
LSD	0.125	4.09	6.27	4.95	0.57	0.54
CV (%)	8.03	23.61	13.32	7.69	56.32	61.61
Pr > F	0.78	0.26	0.83	0.79	0.46	0.80

SD - Soil bulk density; MACRO - Soil macroporosity; MICRO - Soil microporosity; TP - Total soil porosity.
Treatment means followed by the same letters in the column do not differ from each other according to Tukey's test at 5% significance; LSD - Least Significant Difference; CV - coefficient of variation; PR - Penetration Resistance.
Pr > F - Probability of difference according to the F test.

Table 2 shows that soil penetration resistance (PR) did not differ statistically between treatments at either depth; however, values were numerically higher in the silicate treatment in both cases. Castro *et al.,* (2017) found that there was no influence on penetration resistance or soil moisture at any depth greater than 0.4 meters in lime and silicate applications.

Costa *et al.,* (2021) found that treatments with limestone alone or in combination with phosphogypsum had a positive impact on the aggregation and stability of weathered soils, as well as on porosity, especially microporosity, which was influenced in deeper layers. The experiments developed by Emami, Neyshabouri, and Shorafa (2012) verified that treatments with silicate applications showed a variation of 0.05 to 0.34 MPa in soil penetration resistance, which is a positive indicator of decompaction.

CHLOROPHYLL CONCENTRATION

It is observed in Figure 2, through the Tukey test, with 0.05% of significance that the concentrations of chlorophyll a, b, total and carotenoids did not differ statistically between the limestone, silicate and control treatments presented in the experiment. The results were contrary to the studies by Bossolani *et al.,* (2021), who found a significant increase in pigment concentrations

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with increased lime application, as there was better development and distribution of the plant root system, allowing access to nutrients and water in the deeper layers of the soil, mainly Ca and Mg.

Hussain *et al.,* (2021) also found an increase in chlorophyll content in soybean cultivars when silicon was applied via foliar application under normal light and shade conditions, both in monoculture and in intercropping. Nonetheless, the authors verified that carotenoid levels were not significant in treatments with silicon alone in monoculture, a different situation when the factors were evaluated in intercropping, in which they found an increase in pigment levels.

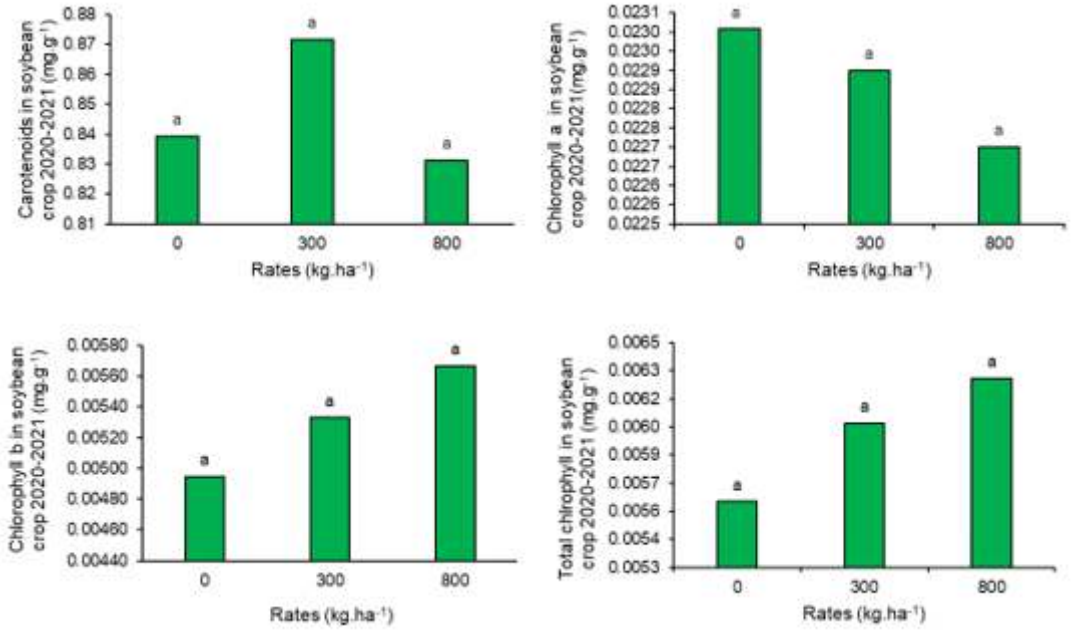


Figure 2. Results of carotenoids, chlorophyll 'a', chlorophyll 'b' and total chlorophyll in soybean crop, 2020-2021 crop
* The averages followed by the same letter, according to the test applied, do not differ from each other.

Considering that the results in Figure 2 were collected during the 2020–2021 crop season, the absence of significant differences is understandable. Precipitation during that season was above the regional average, ruling out drought as a confounding factor. Combined with the early stage of the experiment — in which calcium and magnesium silicate and limestone had not yet had sufficient time to react in the soil — the results presented in Figure 2 are therefore acceptable.

However, when the chlorophyll 'b' concentrations of the soybean crop were evaluated (Figure 3), in the 2022-2023 crop, it was observed that the pigment content was higher in the control than in the limestone treatment. Nevertheless, the silicate treatment did not show a significant difference in relation to the control and limestone. Singh *et al.,* (2022) found that chlorophyll 'b' indices increased in plants under salinity stress when silicon was applied to wheat plants. Islam *et al.,* (2023) also found

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an increase in chlorophyll content in tomato cultivars under soil salinity stress, shortly after calcium applications.

A similar trend was observed for total chlorophyll: the control did not differ statistically from either the silicate or limestone treatment, but comparison between the latter two revealed a relative increase in total chlorophyll levels with soil-applied calcium compared to silicon applications. Studies conducted by Wadas and Dębski (2022) found that when silicon-based biostimulants were used, potato plants under water stress showed an increase in photosynthetic pigments.

Nonetheless, Rachid, Bader, and Al-Alawy (2020) identified that experiments conducted with nanocalcium at 4 ml L^{-1} in cauliflower cultivation obtained selectivity in its action, affecting only carotenoid levels and providing a 20% increase compared to the control treatment. However, the authors' research did not show a significant level when 2 ml L^{-1} of nanocalcium was sprayed on chlorophyll 'a', 'b', totals, and carotenoids.

Finally, carotenoid and chlorophyll 'a' concentrations did not show a significant difference between treatments in this crop year.

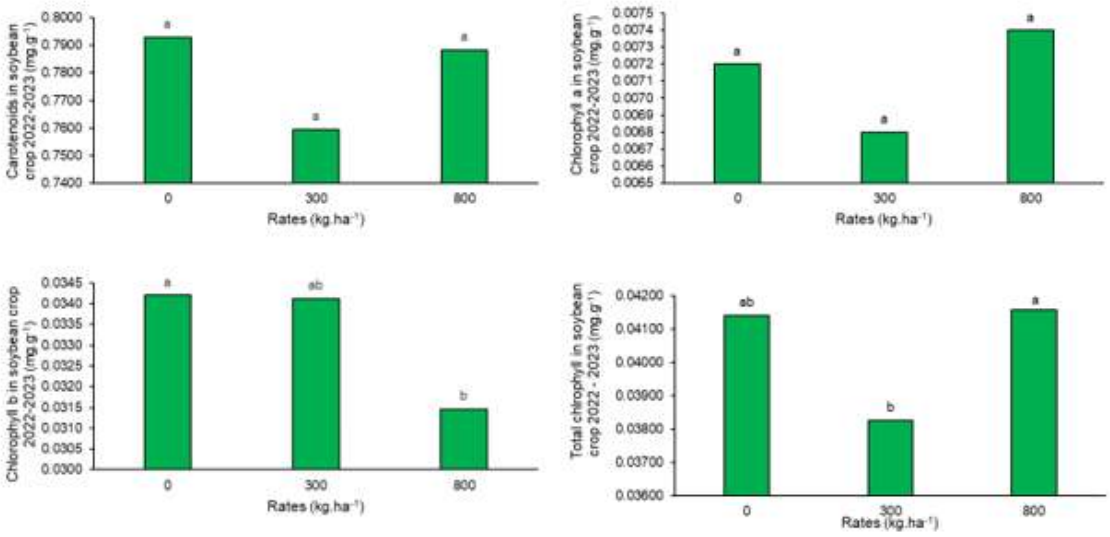


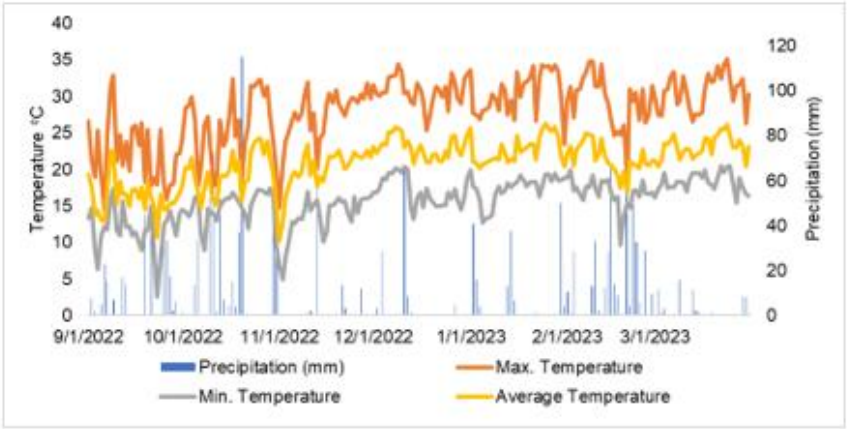
Figure 3: Results of carotenoids, chlorophyll 'a', chlorophyll 'b' and total chlorophyll in soybean cultivation, harvest 2022-2023
* The averages followed by the same letter, according to the test applied, do not differ from each other.

Figure 4 shows the climatic data of precipitation (mm), maximum, average and minimum temperature (ºC), solar radiation (W m^2) and relative air humidity (%), of the Simepar meteorological station, located in Cascavel Pr, 46.8 km away from the experiment site.

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a



b

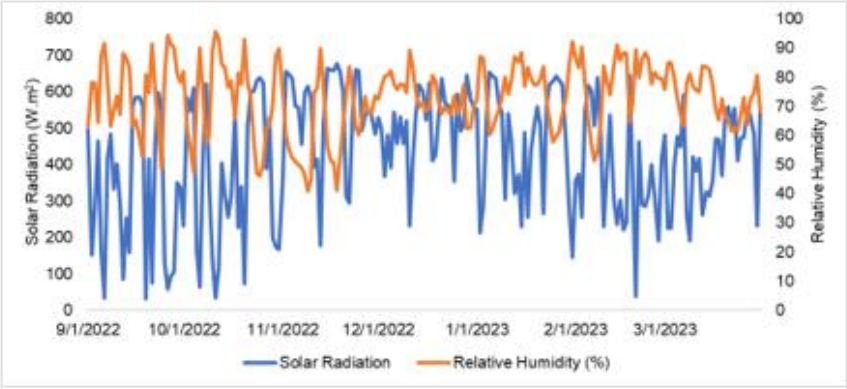


Figure 4. Precipitation results (mm), maximum, average and minimum temperature (ºC)(a), solar radiation (W m^2) and relative air humidity (%) (b), along the soybean crop development cycle for the date 09/01/2022 to 03/30/2023.

Figure 4 shows that solar radiation between November 2022 and February 2023 was irregular, with increases during the period.

Figure 5 shows the values of chlorophyll 'a', chlorophyll 'b', total chlorophyll, and carotenoids in the 2023 second-season corn. It can be seen that the results did not show a significant difference when analyzed using the Tukey test with a 5% probability. Nevertheless, researchers Kaleem *et al.,* (2022) found that corn plants under cadmium stress, when supplied with calcium, showed a significant increase in the concentrations of photosynthetic pigments. This occurred mainly in seedlings immersed in a cadmium concentration of 150 µM, with the application of 10 mM calcium, reflecting a percentage increase of 286.2; 266.0; 215.4, and 140.8% for chlorophyll 'a', chlorophyll 'b', carotenoids, and total chlorophyll, respectively.

Saleem *et al.,* (2022) also observed that foliar applications of silicon (3 mM) increased the content of photosynthetic pigments by 0.026, 0.034, 0.31, and 0.06% in the Sadaf corn cultivar and 0.03, 0.046, 0.42, and 0.08% in the EV-20 cultivar for chlorophyll a, b, total chlorophyll, and

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carotenoids, respectively, in plants grown in sand with toxic cadmium content, when compared to plants grown without silicon application.

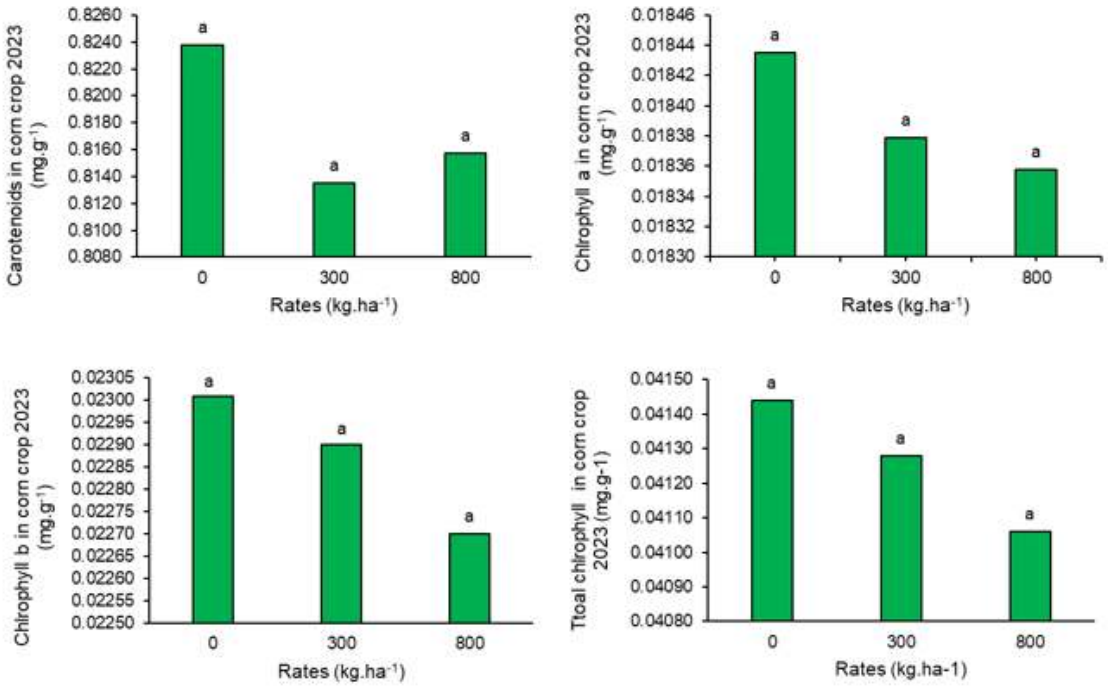


Figure 5. Results of carotenoids, chlorophyll 'a', chlorophyll 'b' and total chlorophyll in corn crop second crop 2023
* The averages followed by the same letter, according to the test applied, do not differ from each other.

AGRICULTURAL PRODUCTIVITY

Table 3 shows the average productivity results for the 2022 wheat harvest and the 2023 second corn harvest. The wheat results show that there was no significant difference between treatments. However, they represent good yields for the crop year, although slightly below the national average for the same agricultural year, which was 3135 kg ha^{-1} (CONAB, 2023). Emran *et al.,* (2024) observed that the treatments in wheat cultivation were satisfactory: when there were four irrigation applications with 400 mg L^{-1} of silicate (highest application rate), the highest values occurred for both grain yield and harvest index.

In turn, Ejigu *et al.,* (2023) found that applications of increasing doses of limestone significantly increased the growth and yield of wheat plants compared to the control. Nonetheless, the authors also found that limestone doses incorporated along the seed row ensured higher crop yields compared to broadcast applications.

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Table 3. Yield results for the 2022 wheat crop and the 2023 second-season corn

Treatment	Wheat	Corn
	----------Kg ha^{-1} ----------	
control	2435.28a	9173.28a
silicate	2760.62a	8677.86a
limestone	2738.99a	8030.92a
Average	2644.96	8627.35
LSD	749.72	1258.38
CV (%)	24.07	12.39
Pr > F	0.49	0.10

Treatment means followed by the same letters in the column do not differ from each other according to Tukey's test at 5% significance; LSD - Least Significant Difference; CV: coefficient of variation.

Corn yields also showed no significant differences between the treatments studied. However, the results obtained are well above the national average, which for the same year was 5,947 kg ha^{-1} (CONAB, 2023). Wakwoya, Woldeyohannis, and Yimamu (2022) verified that different rates of carbonate application showed significant differences in corn ear length, grains per ear, and thousand-grain weight. Positive results were found by Alayafi *et al.,* (2022) when they evaluated corn crop parameters under the effects of salinity. With the application of 2 kg of silicon, they found values with a significant increase in grain yield of up to 36.19 and 36.01%, as well as dry ear weight of up to 27.12 and 27.05% in the first and second harvests of the crop, respectively.

The actual physical conditions of the soil may have been a decisive factor in calcium silicate not revealing its potential to contribute to improving crop yield. The results of the physical properties of the soil prove the excellent management.

Figure 6 shows the climatic data for precipitation (mm), maximum, average, and minimum temperatures (°C), solar radiation (W m^2) and relative air humidity (%) from the Simepar weather station, located in Cascavel, PR, 46.8 km from the experiment site, for the wheat crop, from April 1, 2022, to September 30, 2022.

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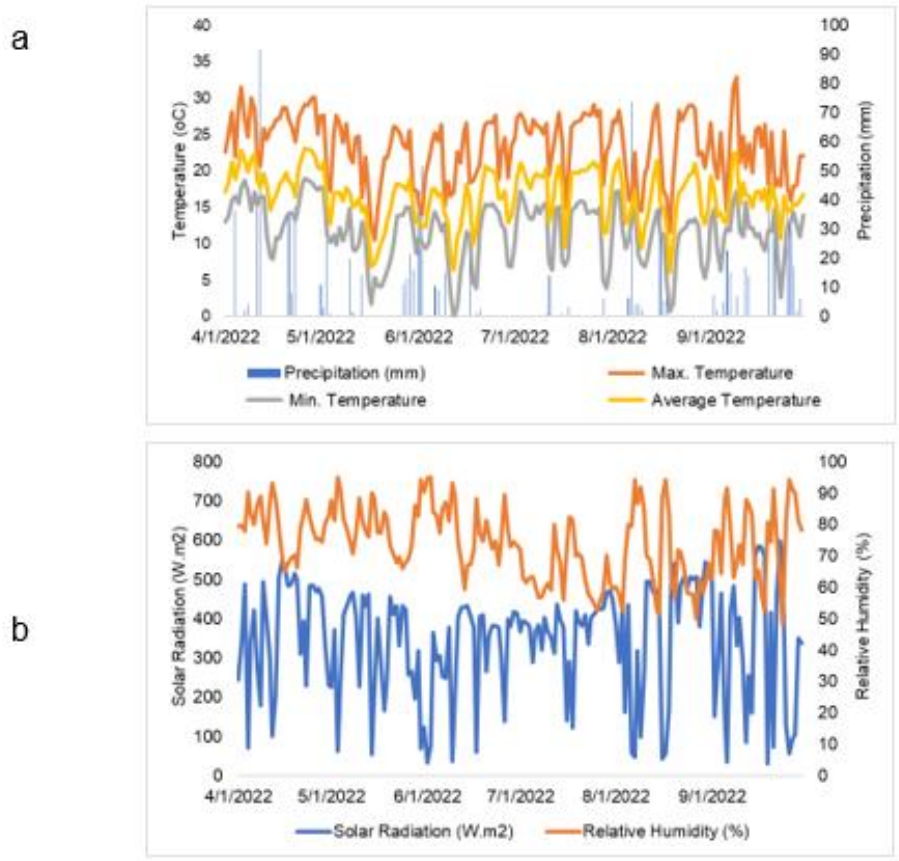


Figure 6. Precipitation results (mm), maximum, average and minimum temperature (ºC)(a), solar radiation (W m^2) and relative air humidity (%) (b), throughout the wheat crop development cycle for the date 01/04/2022 until 01/09/2022.

Figure 6 shows that precipitation throughout the crop cycle was 1022 mm. This represents a higher monthly average rainfall than that cited by Köppen (2019) for the region. Thus, soil moisture conditions are consistent with the productivity shown in Table 3. When evaluating temperature, especially the minimum, there is a longer period with milder temperatures for the month of May, the initial period of the crop, a fact that contributes beneficially to improving crop tillering, also agreeing with the uniformity response in productivity.

Figure 7 shows the climatic data for precipitation (mm), maximum, average, and minimum temperatures (°C), solar radiation (W m^2) and relative air humidity (%) from the Simepar weather station, located in Cascavel, PR, 46.8 km from the experiment site, for the corn crop in the second season of 2023.

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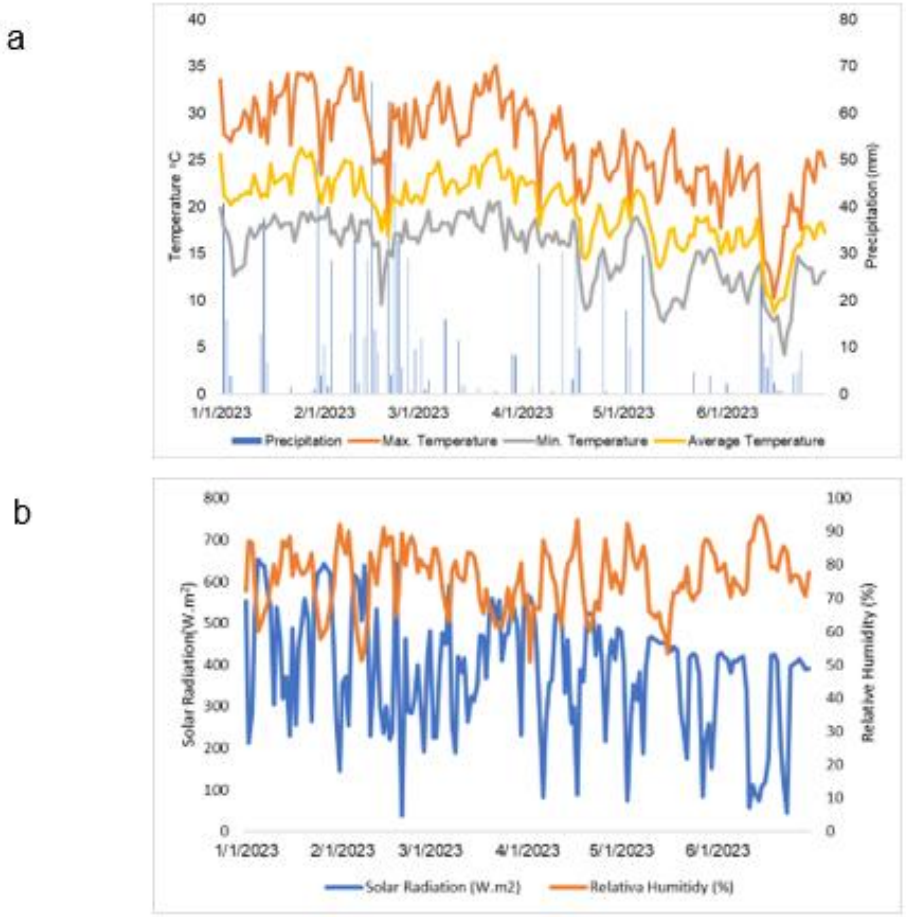


Figure 7. Precipitation results (mm), maximum, average and minimum temperature (ºC)(a), solar radiation (W m^2) and relative air humidity (%) (b), throughout the corn crop development cycle for the date 01/01/2023 to 06/01/2023.

Evaluating Figure 7, especially precipitation, throughout the cycle there was a total of 954 mm, which, when converted to monthly data, yields approximately 159 mm per month. As with wheat, this average precipitation is above the average cited for the region. The responses of wheat and corn yields become understandable when the information from the experiment is gathered: climatological data showing the absence of dry spells, normal soil physical properties, and ideal conditions for very clayey soil, cultural practices, corn hybrids, and wheat cultivars adapted to the study site.

CONCLUSION

The results indicate that wheat and corn yields did not differ significantly among treatments, and that the applied treatments did not improve bulk density, macroporosity, microporosity, or total porosity. Similarly, carotenoid, chlorophyll ‘a’, chlorophyll ‘b’, and total chlorophyll concentrations did

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not differ among treatments. It should be noted that the physical soil properties evaluated were already under ideal conditions prior to the start of the experiment.

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