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Water management and physiological responses of maize plants under the effect of remineralizer

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Abstract: Maize cultivation, which depends on the productive technologies of the cultivars, is heavily dependent on liming and fertilization. Potassium (K) is crucial in soil management, but presents challenges due to its dynamics, high costs and dependence on imports in tropical soils. Remineralizers are ground natural rocks rich in essential minerals and nutrients that improve soil fertility. They can be used as regional alternatives to reduce dependence on imported chemical fertilizers, promoting more sustainable and locally sourced agricultural practices. They can improve physical characteristics, such as water retention, and chemical characteristics, such as nutrient supply, thereby enhancing the water relations in maize. This study analyzed the use of the "*Completo*" remineralizer in a Dystrophic Haplic Cambisol (CXbd) soil (medium-clayey texture) and a Red Dystrophic Oxisol (LVd) (clayey soil), with different K levels (0, 75, and 150 kg K_2O ha^{-1}) and two remineralizer concentrations (4 and 20 Mg ha^{-1}), in a 2x3x2 factorial scheme. The following parameters were evaluated: soil matric potential, soil moisture, water volume, dry matter of the aerial part, photosynthetic rate, transpiration, stomatal conductance, water use efficiency, and xylem water potential. The results showed that the concentration of 4 Mg ha^{-1} of the "*Completo*" remineralizer improved water storage, dry matter content, gas exchange, and xylem water potential in maize plants. The concentration of 20 Mg ha^{-1} was more efficient in CXbd, increasing water use efficiency by 23% and photosynthetic rate by 29%. Each concentration performed better depending on the soil type. We suggest that further research should be conducted to assess the effects of this remineralizer on maize cultivation, due to the complexity of soil-plant-environment interactions.

Keywords; Fertilization management; Food security; K fertilization Soil; Rock dust; Water retention in soil.
Abbreviations: CXbd_Dystrophic Tb Haplic Cambisol; LVd_Dystrophic Red Latosol; K_Potassium.

Introduction

Maize (*Zea mays* L.) is a high-yield crop with significant economic and social relevance (Silva et al., 2023). Cultivated in various countries, it is used for biofuels, animal feed, and human consumption. Brazil is the third-largest producer of maize in the world, behind the United States and China, with an estimated 119 million tons for the 2024/25 harvest (Index mundi, 2024).

The low natural fertility of soils is a limitation for agricultural productivity in Brazil, which relies on the import of fertilizers to maintain production. The country consumes about 7% of global fertilizers, importing 80% of its demand, mainly potassium, phosphorus, and nitrogen (Brasil, 2021). This dependence is linked to the low natural fertility of the main agricultural soils in the country, particularly the Oxisols, Argisols, and Entisols (Santos et al., 2018).

Soil remineralizers, popularly known as "rock dust", are mineral inputs regulated by Law 12.890/2013 and Instruction Normative 05/2016 from the Ministry of Agriculture, Livestock, and Supply, and are already used on about 5 million hectares (Martins et al., 2023). They offer several benefits, such as improving soil health and quality, increasing the availability and efficiency of nutrients, and assisting in carbon sequestration (Manning and Theodoro, 2020; Swoboda et al., 2022). Additionally, they help reduce production costs and dependency on chemical fertilizers, making them a valuable tool for the agricultural sector. The use of remineralizers can modify the chemical, physical, and biological properties of soils, particularly in relation to the application of aluminosilicates (Leite, 1985).

To reduce dependence on imports, it is essential to understand the dynamics of remineralizers in different types of soil, aiming to improve fertilizer management in maize crops. A remineralizer with different characteristics compared to others already available, with a composition based on aluminosilicates, quartz, oxides and organic matter, with significant water retention capacity and presence of electrical charges, has been explored in the region of Riachão das Neves, in the state of Bahia, Brazil. However, little is known about its effects as a soil conditioner.

This study innovates by comparing the effects of two concentrations of the remineralizer "*Completo*", in different soils and K stress, and its influence on soil water and physiological behavior in maize, diverging from studies found in the literature. Therefore, the research aimed to understand how the interaction between remineralizer concentration, soil type and K stress affects soil water storage, gas exchange and xylem water potential in maize plants. The contribution is significant to sustainable agricultural practices, promoting better plant responses under variable soil and climate conditions.

Results

Soil matric potential, soil moisture, and water volume used

The use of 4 Mg ha^{-1} of the remineralizer reduced the matricial water potential in clayey soil (LVd) under severe stress (0 kg K_2O ha^{-1}) by 24%. The medium-clayey texture (CXbd) soil had a matricial potential 50% lower than LVd (Fig. 2A). Under moderate stress (75 kg K_2O ha^{-1}), there was no difference between remineralizer concentrations, but the CXbd showed a 33% reduction in tensions compared to the LVd (Fig. 2B). For the control (150 kg K_2O ha^{-1}), the use of 4 Mg ha^{-1} of the remineralizer significantly reduced the matricial water potential in the CXbd by 16% compared to 20 Mg ha^{-1}, with no significant difference between soil types (Fig. 2C).

Under severe stress (0 kg K_2O ha^{-1}), the use of 4 Mg ha^{-1} of the remineralizer significant increased soil moisture by 6.6% in CXbd and 12% in LVd, compared to 20 Mg ha^{-1}. The CXbd had 17% more moisture than the LVd at both concentrations (Fig. 2D). Under moderate stress (75 kg K_2O ha^{-1}), there was no difference between remineralizer concentrations, but the CXbd had 25% more moisture than the LVd (Fig. 2E). For the control (150 kg K_2O ha^{-1}), there was no difference in soil moisture between remineralizer concentrations and soil types (Fig. 2F).

For the average daily water volume under severe stress (0 kg K_2O ha^{-1}), the use of 4 Mg ha^{-1} of the remineralizer reduced the water volume used in LVd by 36%, while the CXbd had 51% lower water demand than the LVd (Fig. 3A). Under moderate stress (75 kg K_2O ha^{-1}), there was no difference between remineralizer concentrations, but the LVd showed 50.6% higher water demand compared to the CXbd (Fig. 3B). In the control situation (150 kg K_2O ha^{-1}), no significant differences were observed between the soil types and remineralizer concentrations (Fig. 3C).

Dry matter of aerial part

The accumulation of dry matter in maize plants was similar between remineralizer concentrations and soil types under severe stress (0 kg K_2O ha^{-1}). The average found was 56.8 g per plant (Fig. 3D).

Under moderate stress (75 kg K_2O ha^{-1}), 4 Mg ha^{-1} of remineralizer significantly increased dry matter by 11.7% in the CXbd, while 20 Mg ha^{-1} increased it by 13% in the LVd . The CXbd produced, on average, 23% more dry matter than the LVd, with an average value of 69.3 g per plant (Fig. 3E). For the control (150 kg K_2O ha^{-1}), the CXbd showed a significant increase of 13.9% increase in dry matter with the use of 4 Mg ha^{-1} of remineralizer. In the LVd , there was no significant difference between concentrations, with dry matter 21.6% lower compared to CXbd. The average dry matter was 76.9 g per plant (Fig. 3F).

Photosynthetic rate, transpiration rate, and stomatal conductance

In CXbd, the 20 Mg ha^{-1} dose of remineralizer significantly increased the photosynthetic rate of maize by 56.6% under severe stress (0 kg K_2O ha^{-1}). In comparison, the LVd exhibited a photosynthetic rate of 50% higher than the CXbd (Fig. 4A).

Under moderate stress (75 kg K_2O ha^{-1}), 20 Mg ha^{-1} of remineralizer significantly increased the photosynthetic rate by 20% in the CXbd and by 17.7% in the LVd, with the CXbd being 27.5% more efficient than the LVd (Fig. 4B). For the control (150 kg K_2O ha^{-1}), 20 Mg ha^{-1} of remineralizer significantly increased the photosynthetic rate by 11% in the CXbd and by 21.6% in the LVd, with the LVd showing 15.6% lower photosynthetic rate than the CXbd (Fig. 4C).

Under severe K stress in CXbd, 20 Mg ha^{-1} of remineralizer increased transpiration by 26.5%. In LVd, 4 Mg ha^{-1} led to an significant increase of 18.5%. On average, the LVd had 28.9% higher transpiration than the CXbd (Fig. 4D).

Under moderate stress (75 kg K_2O ha^{-1}), 4 Mg ha^{-1} of remineralizer significantly increased leaf transpiration by 15.9% in LVd, while 20 Mg ha^{-1} promoted a 34.5% increase in CXbd. Comparing the soils, the LVd showed a 21.5% increase with 4 Mg ha^{-1} of remineralizer, while the CXbd showed a 28.5% increase with 20 Mg ha^{-1} (Fig. 4E). For the control (150 kg K_2O ha^{-1}), LVd had higher leaf transpiration with 20 Mg ha^{-1} of remineralizer, significantly exceeding the 4 Mg ha^{-1} concentration by 17%. The CXbd was 9% more efficient at the 4 Mg ha^{-1} concentration and 23.9% higher in transpiration than the LVd (Fig. 4F).

Under severe stress (0 kg K_2O ha^{-1}), the CXbd exhibited significantly higher stomatal conductance with 20 Mg ha^{-1} of remineralizer, surpassing the 4 Mg ha^{-1} concentration by 33%. The LVd, on the other hand, exhibited a 42.8% higher conductance than CXbd (Fig. 5A).

Under moderate stress (75 kg K_2O ha^{-1}), 4 Mg ha^{-1} of remineralizer increased stomatal conductance in the LVd by 20% and by 50% in relation to the CXbd. The CXbd, however, showed higher conductance with 20 Mg ha^{-1}, significantly surpassing the 4 Mg ha^{-1} concentration by 50% and the LVd by 20% (Fig. 5B). In the control (150 kg K_2O ha^{-1}), 20 Mg ha^{-1} of

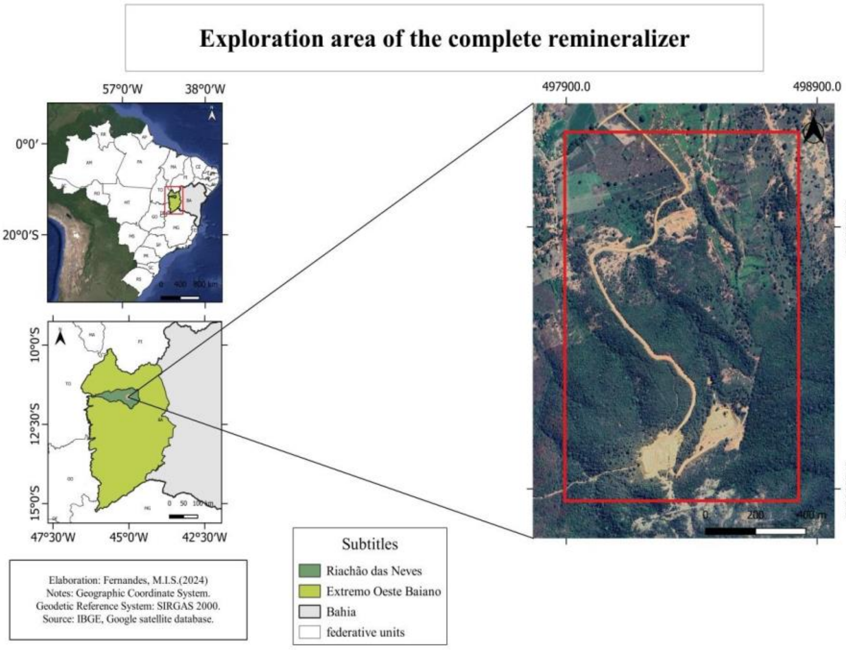

Fig. 1. Exploration area of the "*Complete*" remineralizer.

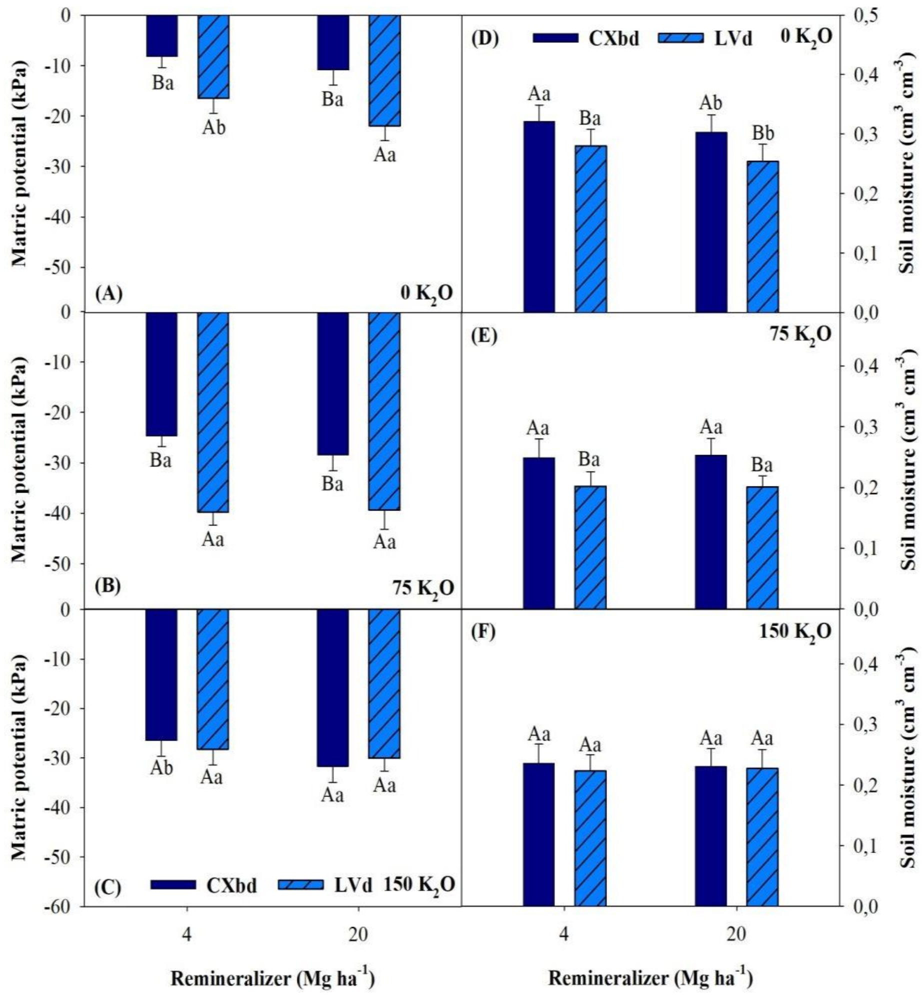

Fig. 2. Mean matric potential and mean soil moisture during the corn production cycle as a function of potassium concentrations, severe stress 0 kg K_2O ha^{-1} (A and D), moderate stress 75 kg K_2O ha^{-1} (B and E) and control 150 kg K_2O ha^{-1} (C and F) and soil type (Cambisolo Háplico Tb Distrófico – CXbd and Latosol Vermelho Distrófico - LVd), for two concentrations of the remineralizer (4 and 20 Mg ha^{-1}). Means with the same capital letters do not differ from each other for the different soil types and means with the same lowercase letters do not differ from each other for the different concentrations of the remineralizer, through the Scott-Knott test ($p < 0.05$). The columns correspond to the means of replicates and standard deviations.

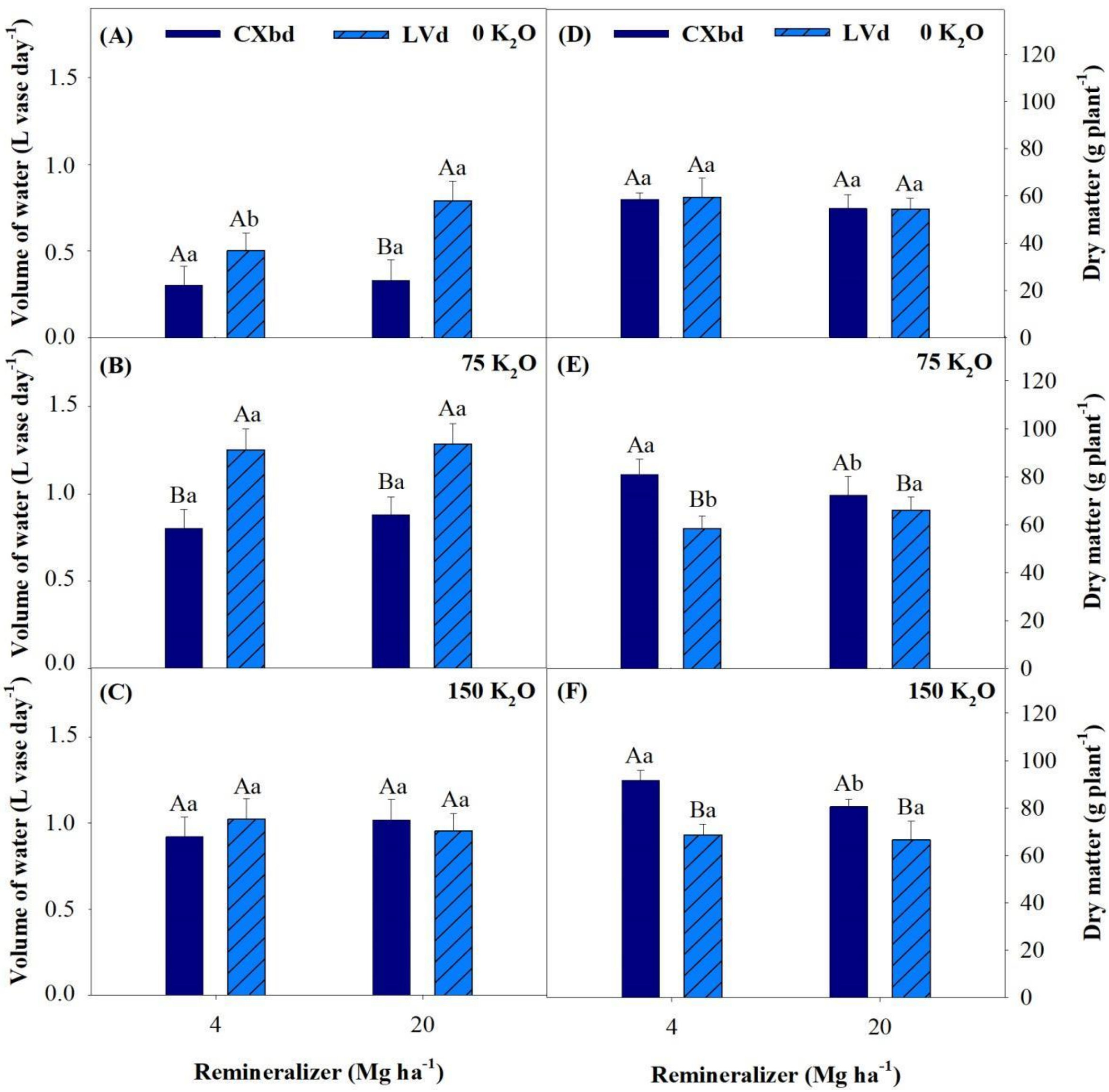

Fig. 3. Average daily volume of water applied to the soil and shoot dry matter during the corn production cycle as a function of potassium concentrations, severe stress 0 kg K_2O ha^{-1} (A and D), moderate stress 75 kg K_2O ha^{-1} (B and E) and control 150 kg K_2O ha^{-1} (C and F) and soil type (Cambisolo Háplico Tb Distrófico – CXbd and Latosol Vermelho Distrófico - LVd), for two concentrations of the remineralizer (4 and 20 Mg ha^{-1}). Means with the same capital letters do not differ from each other for the different soil types and means with the same lowercase letters do not differ from each other for the different concentrations of the remineralizer, through the Scott-Knott test (p < 0.05). The columns correspond to the means of replicates and standard deviations.

remineralizer increased stomatal conductance by 20% in the LVd. In the CXbd, 4 Mg ha^{-1} was 16.6% more effective than 20 Mg ha^{-1} and 40% superior to the LVd (Fig. 5C).

Water Use Efficiency (WUE)

Under severe stress (0 kg K_2O ha^{-1}), the CXbd showed significantly 25% higher water use efficiency with 20 Mg ha^{-1} of remineralizer compared to 4 Mg ha^{-1}, while the LVd showed a 19.4% increase in water use efficiency compared to the CXbd (Fig. 5D).

Under moderate stress (75 kg K_2O ha^{-1}), the LVd showed a significant 36% higher water efficiency with 20 Mg ha^{-1} of remineralizer, while the CXbd exhibited 13% higher efficiency with 4 Mg ha^{-1}, and 34% more efficient than the LVd (Fig. 5E). For the control (150 kg K_2O ha^{-1}), 20 Mg ha^{-1} of remineralizer in CXbd significantly increased water efficiency by 22% compared to 4 Mg ha^{-1} and by 18% compared to the LVd (Fig. 5F).

Xylem water potential

Under severe stress (0 kg K_2O ha^{-1}), no significant differences were observed between remineralizer concentrations and soil types (Fig. 6A). Under moderate stress (75 kg K_2O ha^{-1}), 4 Mg ha^{-1} of remineralizer significantly increased xylem water

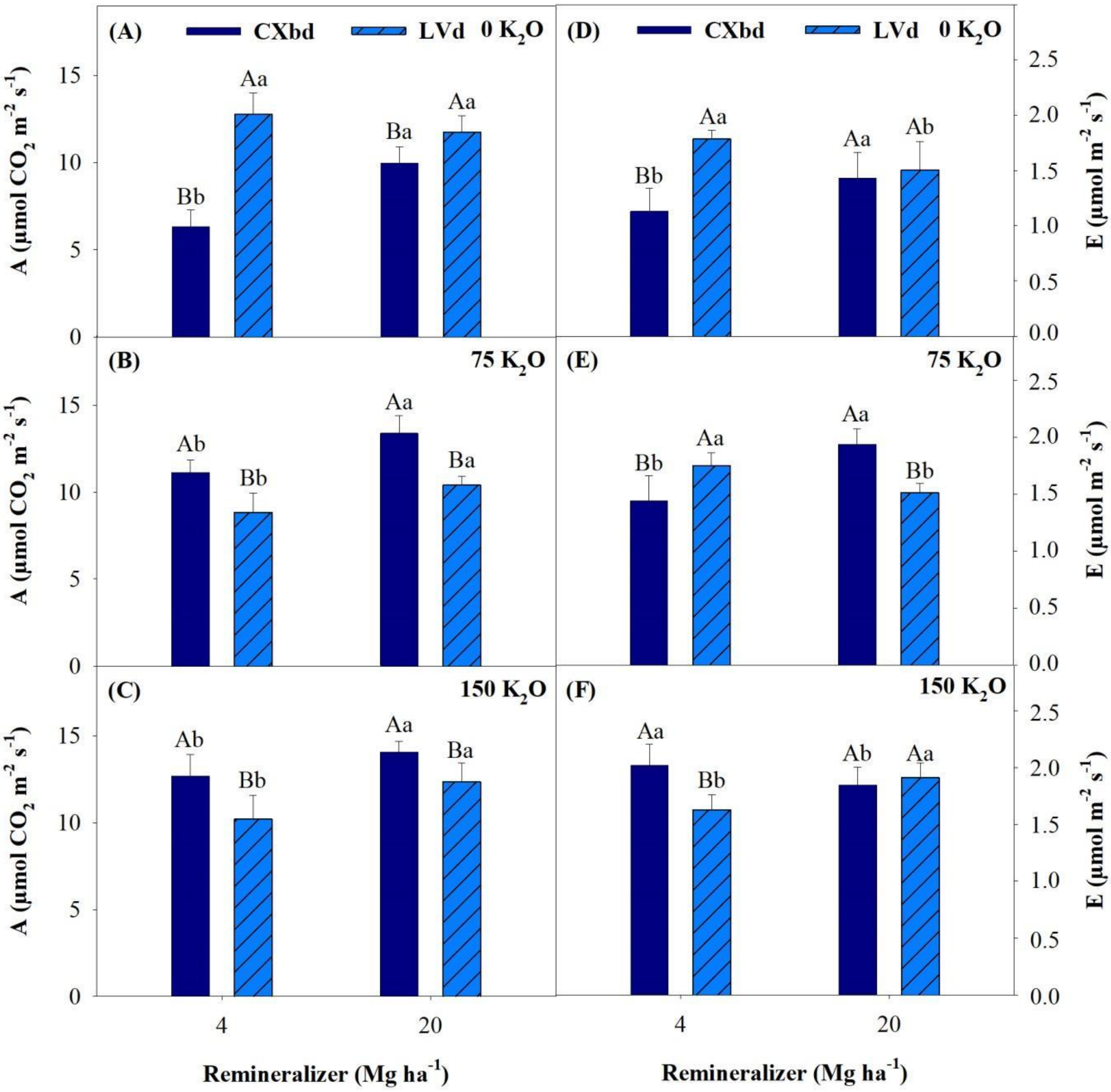

Fig. 4. Photosynthetic rate and transpiration in corn leaves as a function of potassium concentrations, severe stress 0 kg K_2O ha^{-1} (A and D), moderate stress 75 kg K_2O ha^{-1} (B and E) and control 150 kg K_2O ha^{-1} (C and F) and soil type (Cambisolo Háplico Tb Distrófico – CXbd and Latosol Vermelho Distrófico - LVd), for two concentrations of the remineralizer (4 and 20 Mg ha^{-1}). Means with the same capital letters do not differ from each other for the different soil types and means with the same lowercase letters do not differ from each other for the different concentrations of the remineralizer, through the Scott-Knott test ($p < 0.05$). The columns correspond to the means of replicates and standard deviations.

potential by 78% in CXbd and 43% in LVd, while 20 Mg ha^{-1} raised the xylem water potential by 22% in LVd compared to CXbd (Fig. 6B). For the control (150 kg K_2O ha^{-1}), LVd with 4 Mg ha^{-1} of remineralizer increased the xylem water potential by 81% compared to CXbd and 46% compared to 20 Mg ha^{-1}. In the CXbd, 20 Mg ha^{-1} resulted in a significant 26% increase in xylem water potential (Fig. 6C).

Discussion

The remineralizer can be an alternative for soil fertility recovery in various regions of Brazil, due to the variations in the types and textures of tropical soils (Taveira et al., 2021). The LVd and CXbd soils reacted differently to water storage with the use of the remineralizer. Both CXbd and LVd soils showed higher moisture with 4 Mg ha^{-1} of the "*Complete*" remineralizer (Fig. 2D), due to the incorporation of new mineral phases in the soil that have good cation exchange and water retention capacities, improving the soil-plant relationship, enabling greater development (Barbosa Filho et al., 2000), and increasing resistance to water stress (Andrade et al., 2002).

In this study, an interaction between the two soil types (CXbd and LVd) was observed, influencing water storage in the presence of the remineralizer. The LVd showed higher water demand (Reichardt, 1987), while the CXbd exhibited higher matric potential (Klein and Klein, 2015). From a physicochemical perspective, the soil's water storage capacity is explained by the adhesion interactions between water molecules and the cohesion of these molecules at the solid-liquid interface.

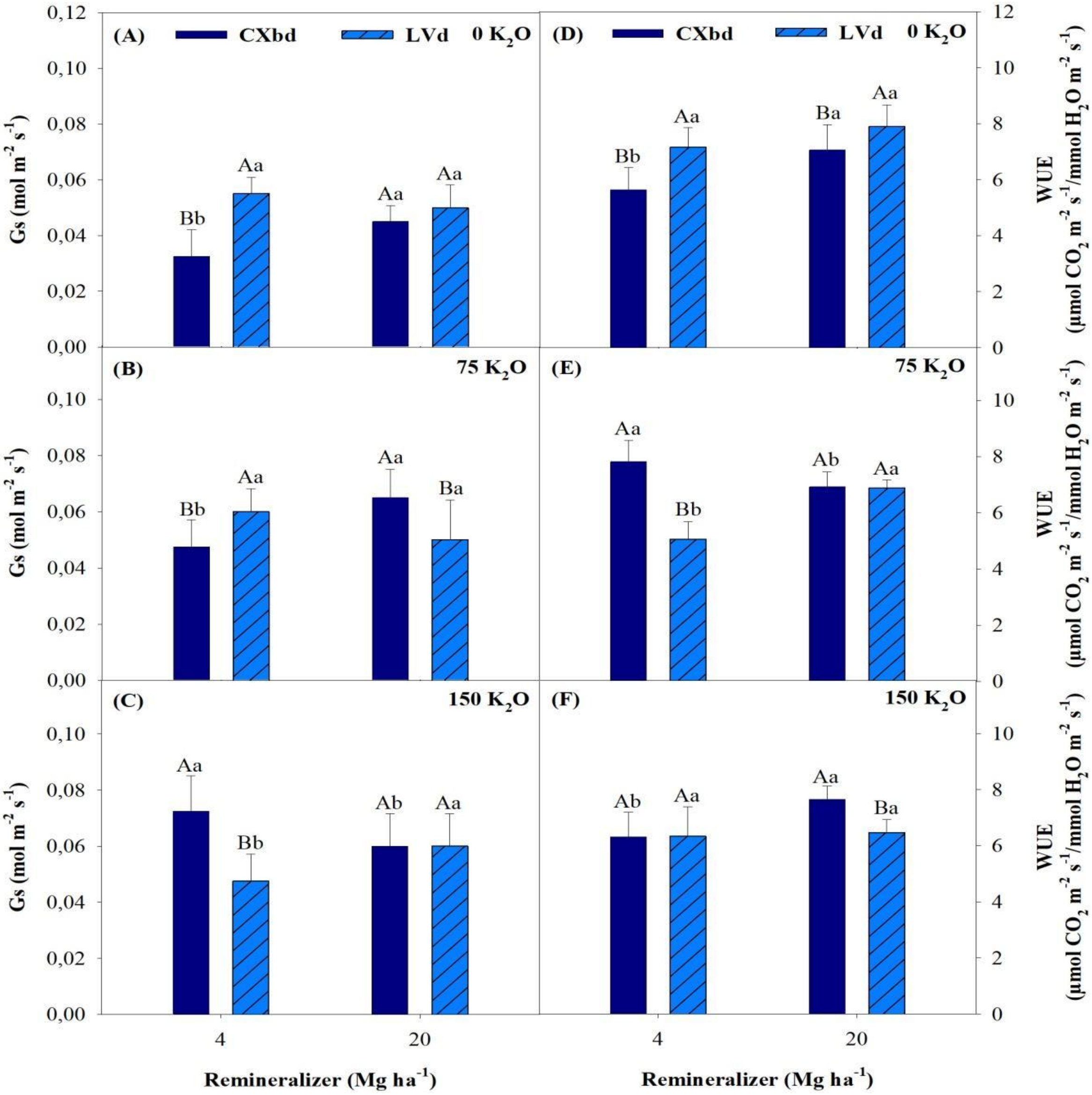

Fig. 5. Stomatal conductance and water use efficiency in corn leaves as a function of potassium concentrations, severe stress 0 kg K_2O ha^{-1} (A and D), moderate stress 75 kg K_2O ha^{-1} (B and E) and control 150 kg K_2O ha^{-1} (C and F) and soil type (Cambisolo Háplico Tb Distrófico – CXbd and Latosol Vermelho Distrófico - LVd), for two concentrations of the remineralizer (4 and 20 Mg ha^{-1}). Means with the same capital letters do not differ from each other for the different soil types and means with the same lowercase letters do not differ from each other for the different concentrations of the remineralizer, through the Scott-Knott test ($p < 0.05$). The columns correspond to the means of replicates and standard deviations.

Remineralizers improve soil quality by increasing nutrient content, reducing acidity, and raising cation exchange capacity (CEC) (Alovisi et al., 2023). They can form 2:1 clay minerals during weathering, resulting in high CEC (Batista et al., 2017), improving nutrient and water retention in the soil.

The accumulation of dry matter in plants is driven by carbon fixation through photosynthesis (Cruz et al., 2010; Durães and Magalhães, 2003). The higher soil moisture in the CXbd (Fig. 2D, E, and F) increased the dry matter production in the shoot of the plants, varying with the increase in available K levels in the soil (Fig. 3D, E, and F). According to Gomes et al. (2018), the accumulation of dry matter in maize plants varies with K levels from the early stages of growth. The combination of higher K content and good water availability favors metabolism and photosynthesis, driving plant growth (Simoes et al., 2020).

The remineralizer used in this research contains K, the second most absorbed macronutrient by maize, essential for activating enzymes involved in photosynthesis and respiration, as well as assisting in the translocation of heavy metals (Foloni and Rosolem, 2008). Adequate K levels improve maize's resistance to water stress, while its deficiency can hinder growth and reduce dry matter accumulation (Meneghette et al., 2019), ultimately affecting productivity.

This research observed that higher concentrations of the remineralizer increased photosynthetic rates, especially in CXbds with lower fertility and lower cation exchange capacity. Low K levels in the soil reduce photosynthesis in plants like cotton (Matsumura et al., 2020) and maize, which depend on K for enzyme activation in photosynthesis (Li et al., 2022).

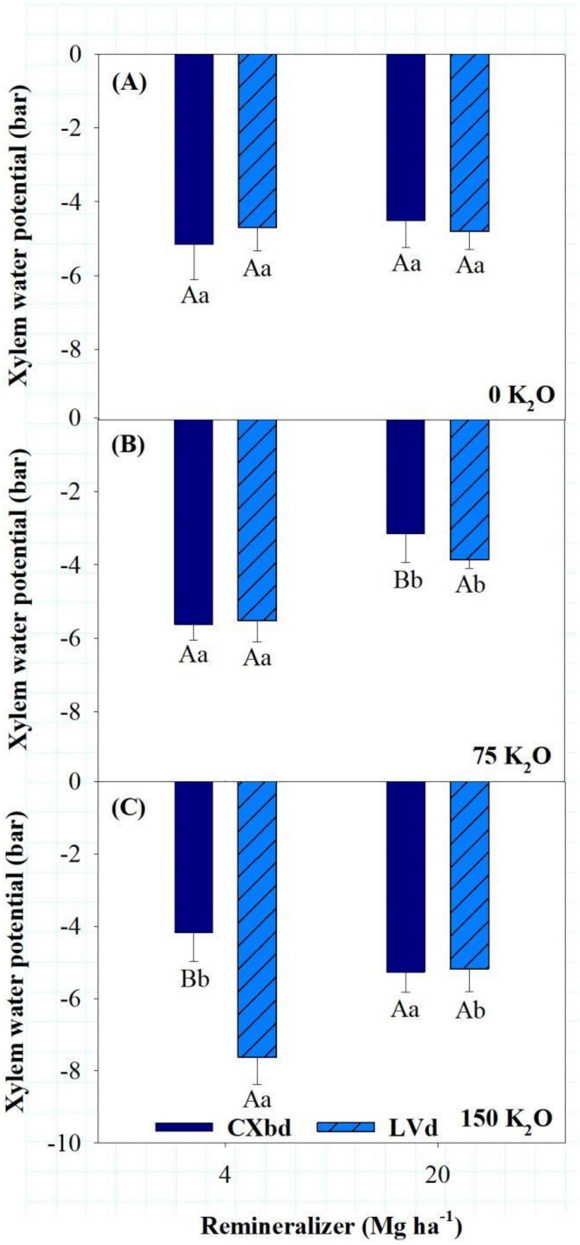

Fig. 6. Xylem water potential of corn plants as a function of potassium concentrations, severe stress 0 kg K_2O ha^{-1} (A), moderate stress 75 kg K_2O ha^{-1} (B) and control 150 kg K_2O ha^{-1} (C) and soil type (Cambisolo Háplico Tb Distrófico – CXbd and Latosol Vermelho Distrófico - LVd), for two concentrations of the remineralizer (4 and 20 Mg ha^{-1}). Means with the same capital letters do not differ from each other for the different soil types and means with the same lowercase letters do not differ from each other for the different concentrations of the remineralizer, through the Scott-Knott test ($p < 0.05$). The columns correspond to the means of replicates and standard deviations.

Similar results were found when there were no changes in gas exchange due to exchangeable cations (Murdi, 2007). The availability of K is essential for the photosynthetic rate (Gazola et al., 2019), especially when combined with magnesium (Mg) (Tränkner et al., 2018), which increases the efficiency of solar radiation conversion (Bergamaschi et al., 2004).

Leaf temperature, due to variations in the environment, influences water vapor loss from leaves and plant transpiration (Taiz and Zeiger, 2013). In CXbd, the severe stress treatment (0 kg K_2O ha^{-1}) resulted in a lower transpiration rate in maize due to low K availability and higher water availability (Fig. 4D). These results support the findings of França et al. (2022), which indicate that K deficiency reduces transpiration, but differ from those found in soybean crops by Souza (2023), who observed that water deficit reduces both transpiration and photosynthetic rate. The application of 20 Mg ha^{-1} of remineralizer increased transpiration in CXbd under both severe and moderate K stress, but did not have the same effect in LVd (Fig. 4D and E).

The increase in K improves stomatal conductance, photosynthesis, and CO_2 uptake by plants (Lu et al., 2017). The lack of K impairs metabolic processes, such as osmotic regulation and the activation of enzymes important for photosynthesis and respiration in plants (Taiz and Zeiger, 2013). High K levels increased stomatal conductance and transpiration, allowing more CO_2 to enter for photosynthesis and greater water loss (Bezerra et al., 2023). The application of 20 Mg ha^{-1} of remineralizer increased stomatal conductance due to the increase in K in the soil under severe stress (0 kg K_2O ha^{-1}) for the CXbd (Fig. 5A and B).

The K plays a critical role in improving water use efficiency by regulating stomatal opening (Taiz and Zeiger, 2013). In this study, the use of 20 Mg ha^{-1} of the "*Completo*" remineralizer improved water efficiency in both soil types. Higher K levels and better water relations enhance water use efficiency. Even in the absence of mineral K, the "*Completo*" remineralizer improved this efficiency under critical K conditions. The K is essential for transpiration and carbon fixation, with similar results found by Siddiqui et al. (2008).

Water potential in plant leaves varies from zero in plants with no water stress to negative values in plants under water deficit. Studies indicate that the ideal water potential for maize leaves ranges between -0.6 and -0.8 MPa (Boyer, 1970). The application of 20 Mg ha^{-1} of the "*Completo*" remineralizer increased the xylem water potential in maize leaves. Plant cells have a positive water potential when turgid, but negative values indicate loss of turgidity due to water shortage (Bianchi et al., 2005).

Stomatal opening is regulated by the entry of K ions into guard cells (Kerbauy, 2012). The efflux of anions depolarizes the cell, opening K channels, increasing water potential, and promoting water loss, which reduces turgidity, leading to stomatal closure (Kerbauy, 2012). The CXbd, having higher moisture content, exhibited higher xylem water potentials, particularly under moderate stress and control conditions. These results reflect trends observed in other variables, underscoring the importance of soil management practices that improve soil structure (Bianchi et al., 2005).

Materials and methods

Study location and growing conditions

The experiment was conducted between November 2022 and June 2023, in an arch-type greenhouse covered with 150 µm plastic film, with the sides protected by anti-thrips screens. The research took place at the Demonstration and Experimental Field (CaDEx) of the Federal University of Uberlândia, Monte Carmelo-MG Campus (18°43'36.26" S; 47°31'28.50" W; 903 m). During the experiment, the internal temperatures of the greenhouse varied from a maximum of 39.9°C, a minimum of 10.1°C, and an average of 24.2°C, with relative humidity ranging from 37.8% to 90.8%.

Plant characteristics

The hybrid used in the research was K7510 Vip3, which offers tolerance to the main species of caterpillars, including the fall armyworm (*Spodoptera frugiperda*). Its agronomic characteristics include a plant height of 260-280 cm, with ear insertion between 125-145 cm, semi-erect architecture, white cob, and yellow-orange, semi-dented grains. The weight of 1.000 seeds (PMS) ranges from 310-350 g. This hybrid is dual-purpose for grains and silage and is highly adaptable for second-crop cultivation (KWS, 2024).

Soil characteristics

Two types of soils were used in this research: Red Dystrophic Oxisol (LVd) with a clayey texture, collected from native forest, and Dystrophic Haplic Cambisol (CXbd) with a medium-clayey texture, collected from natural field. The soils were collected at a depth of 0 to 20 cm. The samples were air-dried and passed through a 2.0 mm mesh sieve, then homogenized for chemical and physical characterization (Table 1). The granulometric analysis was performed according to Teixeira et al. (2017).

The calculations for soil acidity correction aiming to increase Ca^{2+} and Mg^{2+} levels and neutralize Al^{3+}. The limestone used was of the dolomitic type, containing 45 to 48% calcium oxide and 6 to 8% magnesium oxide, relative efficiency (ER) = 92.5%, neutralization power (PN) = 100% and real total neutralization power (PRNT): 92.5%, which was applied and mixed with the soil.

After homogenization, the soil was moistened and incubated for 45 days to favor the corrective reaction. One plant was grown per pot with a volume of 14 dm^3 of soil. Fertilization for macronutrients and micronutrients was based on the recommended rates by Marques et al. (2022) (Table 2).

The K supply was considered a factor within the experiment, with three concentrations: severe stress (0 kg K_2O ha^{-1}), moderate stress (75 kg K_2O ha^{-1}) and control (150 kg K_2O ha^{-1}). KCl (60% K_2O) was used as the potassium (K) source. The treatments were applied by incorporating the sources into the soils as base fertilizer, 40 days after the corrective incubation.

Characteristics of the "Complete" remineralizer

The remineralizer used was extracted in the region of Riachão das Neves-BA, by the company Geofértil Mineradora LTDA and characterized as "Complete" (Fig. 1). The geological formation is composed predominantly of siltstones, sandstones and arkoses, with a green to grayish-green coloration.

Its mineralogical composition is dominated by aluminosilicates, quartz and oxides. The material has a water retention capacity of 30.2% and a cation exchange capacity (CEC) of 8.52 cmol kg^{-1}. The mineralogical compositions of the remineralizer are detailed in Table 3.

The chemical composition of the "*Complete*" remineralizer contains: 4.2% K_2O, 1.7% CaO, 3.2% MgO, 59.3% SiO_2, 19.2% Al_2O_3, 9.1% Fe_2O_3 and 3.3% other elements.

Table 1. Chemical and physical characteristics of soils (LVd and CXbd) at a depth of 0-20 cm before planting fertilization[1] and after the experiment[2].

Chemical[3]	Unit	[1]LVd	[2]LVd	[1]CXbd	[2]CXbd
pH $CaCl_2$		04.55	06.20	04.27	06.30
P	mg dm^{-3}	00.35	360.00	00.59	324.00
K	mg dm^{-3}	21.75	76.73	27.22	49.75
Ca	$cmol_c$ dm^{-3}	00.41	02.72	00.33	03.29
Mg	$cmol_c$ dm^{-3}	00.13	00.64	00.20	00.47
Al	$cmol_c$ dm^{-3}	00.10	00.00	00.41	00.00
H+Al	$cmol_c$ dm^{-3}	02.48	01.90	04.13	01.84
Sum of bases	$cmol_c$ dm^{-3}	00.60	03.56	00.60	03.89
t	$cmol_c$ dm^{-3}	00.70	03.56	01.01	03.89
T	$cmol_c$ dm^{-3}	03.08	05.46	04.73	05.73
V	%	19.00	65.00	13.00	68.00
m	%	00.00	00.00	41.00	00.00
MO	dag kg^{-1}	00.88	00.86	01.66	01.19
B	mg dm^{-3}	00.10	00.14	00.16	00.15
Cu	mg dm^{-3}	00.82	00.95	01.16	01.65
Fe	mg dm^{-3}	28.52	29.80	50.10	58.00
Mn	mg dm^{-3}	09.27	02.83	11.84	04.88
Zn	mg dm^{-3}	00.37	02.20	00.62	03.35
Physical[4]					
Sand	g kg^{-1}	370.00		670.00	
Silt	g kg^{-1}	90.00		20.00	
Clay	g kg^{-1}	540.00		310.00	

3 pH (active acidity) - Method: CaCl2 0.01 mol.L-1; H+Al (potential acidity) - Method: SMP pH; Exchangeable aluminum - Method: Titrimetry (1 mol.L-1); Organic matter (OM) - Method: Colorimetric (IAC); Phosphorus, Potassium, Calcium and Magnesium - Method: Ion exchange resin; S-SO42- (Sulfur) - Method: Turbidimetry (BaCl2 powder); Fe, Mn, Cu and Zn - Method: DTPA (Atomic Absorption); Boron: BaCl2.2H2O - Method: microwave. 4 Soil physical analysis: Densimeter method. Teixeira (2017). Dystrophic Red Latosol (LVd) and Dystrophic Tb Haplic Cambisol.(CXbd).

Table 2. Nutrients, recommended amounts and sources used in fertilizing maize plants.

Nutrients	Concentrations (mg kg of soil^{-1})	Sources
N	300	CH_4N_2O
P	300	$NH_4H_2PO_4$
S	50	$MgSO_4 \cdot 7H_2O$
Mg	46	$MgSO_4 \cdot 7H_2O$
Mn	3.0	$MnSO_4$
B	2.5	H_3BO_3
Cu	7.5	$CuSO_4 \cdot 5H_2O$
Mo	0.5	$(NH_4)_6Mo_7O_{24} \cdot 4\ H_2O$
Zn	2.5	$ZnSO_4 \cdot 7H_2O$

Table 3. Mineralogical composition of the "*Complete*" remineralizer.

Component name	Composition (%)	Chemical formula
Quartz	10.37	SiO_2
Muscovite	45.90	$K, Al_2(Al, Si_3O_{10})(F,OH)_2$
Clinochlore	12.54	$(Mg_5Al)(Al, Si_3)\ O_{10}\ (OH)_8$
Vermiculite	13.12	$(Mg, Fe)_3\ [(Si, Al)_4\ O_{10}][\ OH]_2\ 4H_2O$
Kaolinite	6.42	$Al_2O_3\ 2SiO_2\ 2H_2O$
Goethite	3.75	FeO (OH)
Rutile	0.93	TiO_2
Greenalite	6.97	$Fe_3\ Si_2\ O_5\ (OH)_4$
Total	100.00	

The mineralogical composition was calculated from the chemical composition of the rock, determined by X-ray fluorescence spectrophotometry.

Irrigation management

The irrigation of the experiment was carried out with a semi-automated system, using flexible tubes, self-compensating drippers and anti-drainage devices with a flow rate of 2.3 L h^{-1}. The system was controlled using an ESP-ME3-RainBird panel, ensuring precision in the supply of water to the maize crop throughout its cycle.

Water management was carried out by monitoring the potential of the soil water matrix using tensiometers. Moisture was determined using the water retention curve, specific for the CXbd and LVd soils. The curve was obtained at several pressure points and adjusted to the model of van Genuchten (1980), using the SWRC program (Dourado-Neto et al., 2000). The estimated field capacity for the pots was 0.31 $cm^3\ cm^{-3}$ for CXbd and 0.30 $cm^3\ cm^{-3}$ for LVd. Daily monitoring of the tensiometers was performed to estimate the current moisture content, the volume of water required to return the pot to field capacity and the irrigation time.

Experimental design

The experiment was conducted in a 2×3×2 factorial design with four replications, considering: two soil types: Dystrophic Red Latosol (LVd) and Dystrophic Tb Haplic Cambisol (CXbd), three potassium (K) concentrations, severe stress (0 kg K_2O ha^{-1}), moderate stress (75 kg K_2O ha^{-1}) and control (150 kg K_2O ha^{-1}); and two concentrations of the remineralizer (4 and 20 Mg ha^{-1}). The remineralizer and K was applied and incorporated into the entire soil volume 40 days after corrective incubation.

Soil matric potential, soil moisture and volume of water used

The soil matric potential was assessed daily using means of tensiometer readings installed in each treatment, taken between 17:00 and 18:00, and expressed in KPa. Soil moisture was calculated from these readings using the van Genuchten equation. The volume of water used in the experiment was determined using the operating time of the irrigation system and the flow rate of the drippers, with the result expressed in liters.

Dry matter of aerial part

The maize plants were cut at ground level and dried in an oven at 65°C until they reached constant mass. After drying, the material was weighed on a semi-analytical digital balance (model UX6200H: 6200 g x 0.01 g, Shimadzu, Kyoto, Japan) and the mass was recorded in grams.

Photosynthetic rate, transpiration rate and stomatal conductance

The rates of net photosynthesis per leaf area (A), leaf transpiration (E) and stomatal conductance to water vapor (Gs) were determined from the CO_2 variations, using a portable LC pro-SD meter LI-6400-02B chamber. The intensity of photosynthetically active radiation was fixed at 1,000 mmol $m^{-2}\ s^{-1}$, measurements were taken in the morning, between 8 and 9 am, using the diagnostic leaf below and opposite the spike with the plant in stage R1.

Quantification of physiological water use efficiency (WUE)

Water use efficiency was estimated using the relationship between photosynthesis (μmol $CO_2\ m^{-2}\ s^{-1}$) and transpiration (mmol $H_2O\ m^{-2}\ s^{-1}$) of the crop according to equation 1, physiologically representing the WUE (Banziger et al., 2000).

Eq. 1:

$$WUE = \frac{A}{E} \qquad (1)$$

Where:
WUE – Water use efficiency (mol CO_2 mol H_2O^{-1})
A – Photosynthetic rate (μmol $CO_2\ m^{-2}\ s^{-1}$).
E – Leaf transpiration rate (mmol $H_2O\ m^{-2}\ s^{-1}$)

Xylem water potential

The xylem water potential in the leaf was measured using the Scholander pump method, which evaluates the hydrostatic pressure of the sap in the xylem (Guimarães and Stone, 2008; Scholander et al., 1965). Collections were performed between 03:00 and 04:00 hours, in the absence of light, with fully expanded leaves at the R1 phenological stage. The leaves were placed in plastic bags and stored in thermal boxes with ice and aluminum foil to maintain cooling and avoid light.

Data analysis

The experimental data were subjected to analysis of variance and, when significant differences were found, the Scott-Knott test was applied at a 5% probability level. Standard errors were calculated for all means. All statistical procedures were performed using the Sisvar software (Ferreira, 2019).

Conclusion

It was concluded that the application of 4 Mg ha^{-1} of the "*Completo*" remineralizer improved water retention, dry matter content, gas exchange and xylem water potential in maize plants. The concentration of 20 Mg ha^{-1} of the "*Completo*" remineralizer showed better water use efficiency in LVd and CXbd soils, contributing to sustainable agricultural practices.
We suggest that future research be conducted to evaluate the effects of new concentrations of the remineralizer and cultivation of other species in different soils, due to the complexity of soil-plant-environment interactions.

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Author Contribution Statement (CRediT)

DJM was the advisor of this research, coordinating the analysis, methodology, and statistics. MISF conducted the experiment in the greenhouse, assessing hydric, anatomical, physiological, biochemical, and morphological parameters. EIM, RRA AVD, LGN, MCC, WOS, and FPA assisted in the research analysis.

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