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# Soil acidity levels for blackberry liming recommendation and yield increase

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**Abstract** – The objective of this work was to determine the acidity levels to obtain adequate soil chemical attributes for the maximum fruit yield of blackberry trees grown in acidic soils subjected to increasing limestone rates. The BRS Tupy, Brazos, Guarani, and BRS Xavante blackberry cultivars were evaluated on the Typic Hapludox (LVdf) and Rhodic Hapludox (LVd) soils, to which four rates of dolomitic limestone were applied (0, 1.5, 3.0, and 6.0 Mg ha$^{-1}$). The effect of liming on soil chemical attributes, in a 2×4 factorial arrangement (soils and limestone rates), as well as leaf nutrient content and fruit yield, in a 2×4×4 factorial arrangement (soils, limestone rates, and cultivars), were evaluated. The maximum fruit yield was obtained with 3.3 Mg ha$^{-1}$ dolomitic limestone. The blackberry cultivars showed a high demand for Ca, Mg, and base saturation and a low tolerance to aluminum in the soils. From 3.3 Mg ha$^{-1}$ dolomitic limestone, the maximum fruit yield of blackberry trees grown in acidic soils is obtained with pH 5.6, maximum tolerated aluminum saturation of 6%, Ca and Mg concentration of 45.3 mmol$_c$ kg$^{-1}$, and base saturation of 48.3%.

**Index terms**: *Rubus*, aluminum, base saturation, nutritional efficiency, soil acidity, soil pH.

## Níveis de acidez do solo para recomendação de calagem e aumento de produção da amora-preta

**Resumo** – O objetivo deste trabalho foi determinar os níveis de acidez para obter os atributos químicos do solo adequados à máxima produção de frutos de amoreiras-pretas cultivadas em solos ácidos submetidos a doses crescentes de calcário. Foram avaliadas as cultivares de amoreira-preta BRS Tupy, Brazos, Guarani e BRS Xavante nos solos Latossolo Vermelho Distroférico (LVdf) e Latossolo Vermelho distrófico (LVd), aos quais foram aplicadas quatro doses de calcário dolomítico (0, 1,5, 3,0 e 6,0 Mg ha$^{-1}$). Foram avaliados o efeito da calagem sobre os atributos químicos do solo, em arranjo fatorial 2×4 (solos e doses de calcário), bem como o teor de nutrientes foliares e a produção de frutos, em arranjo fatorial 2×4×4 (solos, doses de calcário e cultivares). A produção máxima de frutos foi obtida com 3,3 Mg ha$^{-1}$ de calcário dolomítico. As cultivares de amoreira-preta apresentaram alta demanda por Ca, Mg e saturação por bases e baixa tolerância ao alumínio nos solos. A partir de 3,3 Mg ha$^{-1}$ de calcário dolomítico, a produção máxima de frutos de amoras-pretas cultivadas em solos ácidos é obtida com pH 5,6, saturação máxima tolerada de alumínio de 6%, concentração de Ca e Mg de 45,3 mmol$_c$ kg$^{-1}$ e saturação por bases de 48,3%.

**Termos para indexação**: *Rubus*, alumínio, saturação por bases, eficiência nutricional, acidez do solo, pH do solo.

## Introduction

Although blackberry is native to temperate climates, it is also well adapted to subtropical regions, where it shows a good yield (Curi et al., 2015; Croge et al., 2016; Oliveira et al., 2017). However, the expansion of the cultivation of this species in regions without a cold winter is still recent, requiring information and updates mainly on the development and nutritional management of different cultivars due to the increase in their vegetative growth and differences in their production cycles observed in these locations, which possibly justifies the need of adjusting nutrient recommendations (Campagnolo & Pio, 2012b; Teixeira et al., 2021).

Since blackberries are cultivated in different soil types, it is important to determine nutrient availability using indicators of soil quality, such as pH value (Bieganowski et al., 2013; Kobierski et al., 2015). In the case of blackberries, a wide pH range is tolerated, but there is a specific pH considered ideal for each crop to reach its maximum productive potential (Strik & Finn, 2012). In Brazil, due to the lack of studies defining the adequate soil acidity levels to calculate liming requirements for blackberries, the pH values used to grow the crop are those recommended in other countries. However, this means that the different types of Brazilian soils (mostly acidic) that may be influencing the productive potential of the species are not being considered.

According to Li et al. (2019), acidic soils cause the loss of basic cations, an increase in aluminum saturation, and a decline in crop yield. In this context, liming is one of the most important techniques for changing soil pH by increasing pH values, calcium, and magnesium and decreasing Al, which balances the cations within the soil (Rietra et al., 2017; Li et al., 2019) and increases the availability of essential nutrients for plants, improving crop growth and yield (Bhat et al., 2010; Sikiric et al., 2011). However, the response of different crops depends on their tolerance to Al and the decrease in soil acidity (Holland et al., 2019).

In addition to pH, base saturation, a general indicator of soil condition, can influence nutrient interaction and availability (Silva et al., 2016b), which are also improved after limestone application. Braga Neto et al. (2019), for example, found that physalis (*Physalis peruviana* L.) reached its maximum development after the application of 1.8 Mg $ha^{-1}$ limestone, which increased soil base saturation to 67%. In a study with physic nut (*Jatropha curcas* L.), Silva et al. (2016a) observed maximum plant growth when 1.05 g $kg^{-1}$ limestone was applied, increasing water pH to above 6.0 and base saturation to 52%. Gilliam et al. (2018) added that, coupled to the soil analysis, leaf nutrient concentrations are often useful to evaluate soil fertility and plant-soil interactions.

Regarding the recommended dolomitic limestone rates, according to the Schumacher McLean & Pratt (SMP) index, commonly used throughout the United States for liming of blackberry crops, from 2.0 to 4.0 Mg $ha^{-1}$ should be applied to acidic soils with low Ca and Mg concentrations (Hall & Funt, 2017). In Brazil, it is recommended to mix from 0.3 to 0.5 kg limestone in the planting hole and to spread a maximum of 3.0 Mg $ha^{-1}$ on the surface area of the soil (Pagot et al., 2007), which should be done at least three months before the installation of the orchard to raise soil pH to 5.5 within the layer from 0 to 0.20 m of depth (Silva et al., 2016b). However, there is no mention of other parameters, such as expected base saturation, maximum Al saturation tolerated, or Ca and Mg requirements for the blackberry crop. In relation to the SMP index, increasing base saturation has the advantage of adapting to different crops according to their requirements (Raij, 2011), as well as of neutralizing Al and increasing Ca and Mg.

The objective of this work was to determine the acidity levels to obtain adequate soil chemical attributes for the maximum fruit yield of blackberry trees grown in acidic soils subjected to increasing limestone rates.

## Materials and Methods

The experiment was carried out in a greenhouse located in the fruit orchard of Universidade Federal dos Vales dos Jequitinhonha e Mucuri, in the municipality of Diamantina, in the state of Minas Gerais, Brazil. The greenhouse had 4.70 by 7.70 m dimensions, with a height of 6.0 m, to allow of a maximum control of pot humidity, and was covered with a 150 µ transparent plastic canvas (two sides and the roof) and smooth-wire meshes, with a 5.0 mm diameter (the other two sides).

The experiment lasted eight months, from May 2019 to January 2020, covering one plant productive cycle. During the experimental period, data on maximum, average, and minimum monthly temperatures were collected through the automatic meteorological station of Instituto Nacional de Meteorologia in Diamantina, located 14 km from the experimental area (Figure 1).

The experimental design was a randomized complete block with three replicates. For the effect of liming on soil chemical attributes, the evaluations followed a 2×4 factorial arrangement (two types of soil and four rates of limestone). To determine maximum fruit yield and plant nutrition, the evaluations followed a 2×4×4 factorial arrangement (two types of soil, four cultivars, and four rates of limestone).

The soils used for planting were a Latossolo Vermelho distroférrico (LVdf) and a Latossolo Vermelho distrófico (LVd) according to the Brazilian soil classification system (Santos et al., 2018), which are equivalent to a Typic Hapludox and Rhodic Hapludox, respectively, both belonging to the Oxisol order (Soil Survey Staff, 2010). Soil samples were collected homogeneously, air-dried, and sieved through a 2.0 mm mesh (Table 1), meeting all the requirements for fine chemical and soil texture analyses, which were performed according to Teixeira et al. (2017).

Considering that cold is an important factor during the dormancy period of blackberry, the cultivars used in the study were BRS Tupy, Brazos, BRS Xavante, and Guarani, which are less demanding regarding low temperatures and have a good sprouting rate.

The cultivated seedlings were obtained from root cuttings due to their greater rooting potential (Campagnolo & Pio, 2012a). The root cuttings were collected at the same time from plants of the pomology sector of Universidade Federal dos Vales dos Jequitinhonha e Mucuri and were grown in 80×150 mm plastic bags containing the Bioplant Plus commercial substrate (Bioplant, Nova Ponte, MG, Brazil). The seedlings were kept in these bags for ten months under micro-sprinkler irrigation at a flow rate of 1.2 L $h^{-1}$, during 10 min, three times a day, until reaching an average height of 0.25 m and diameter of 3.0 mm when they were transferred to pots. Each pot, without holes and lined with transparent plastic bags to avoid the loss of water or any nutrient, contained 3.0 kg of dry soil sieved through 5.0 mm.

Dolomitic limestone, consisting of 380 g $kg^{-1}$ calcium oxide (CaO), 125 g $kg^{-1}$ magnesium oxide (MgO), and 90% effective calcium carbonate equivalent, was

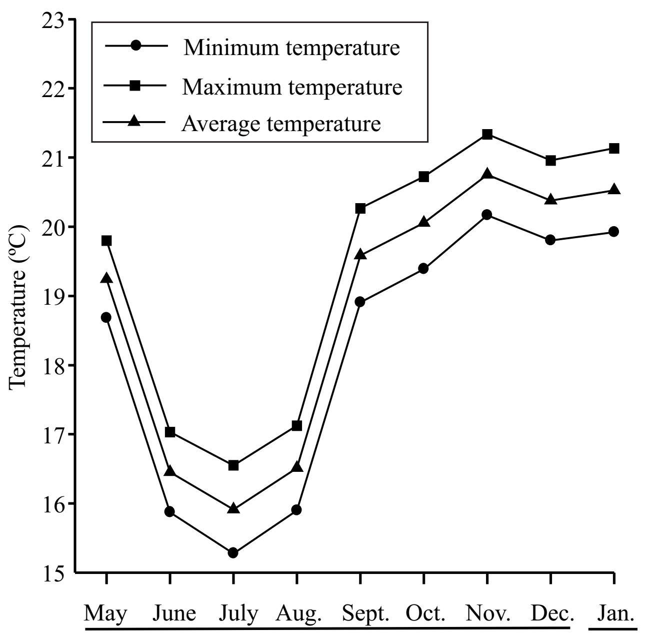


**Figure 1.** Monthly distribution of maximum, average, and minimum temperatures in the experimental period, from May 2019 to January 2020, in the municipality of Diamantina, in the state of Minas Gerais, Brazil.

**Table 1.** Chemical characterization of the acidic soils used in the experiments before treatments.

| Attribute | Unit | LVdf[(1)] | LVd[(2)] |
|---|---|---|---|
| pH (water 1:2.5) | - | 4.20 | 4.01 |
| P (Mehlich 1) | (mg $kg^{-1}$) | 0.30 | 3.16 |
| K (Mehlich 1) | ($mmol_c$ $kg^{-1}$) | 0.03 | 0.02 |
| Ca (KCl 1.0 mol $L^{-1}$) | ($mmol_c$ $kg^{-1}$) | 0.90 | 1.00 |
| Mg (KCl 1.0 mol $L^{-1}$) | ($mmol_c$ $kg^{-1}$) | 0.90 | 0.70 |
| Al (KCl 1.0 mol $L^{-1}$) | ($mmol_c$ $kg^{-1}$) | 21.10 | 20.10 |
| Cation exchange capacity | ($mmol_c$ $kg^{-1}$) | 156.40 | 170.10 |
| Al saturation | (%) | 92.01 | 92.09 |
| Base saturation | (%) | 1.17 | 1.01 |
| Ca saturation | (%) | 0.58 | 0.59 |
| Mg saturation | (%) | 0.58 | 0.41 |
| K saturation | (%) | 0.02 | 0.01 |
| Organic carbon | (g $kg^{-1}$) | 13.51 | 14.73 |
| Remaining P | (mg $L^{-1}$) | 16.88 | 15.89 |
| Sand (pipette method) | (g $kg^{-1}$) | 456 | 377 |
| Loam (pipette method) | (g $kg^{-1}$) | 84 | 63 |
| Clay (pipette method) | (g $kg^{-1}$) | 460 | 560 |

(1)LVdf, Latossolo Vermelho distroférico, i.e., a Typic Hapludox. (2)LVd, Latossolo Vermelho distrófico, i.e., a Rhodic Hapludox.

applied to both soils. The application rates aimed at increasing soil pH to 5.5, which is recommended for blackberries grown in the states of Rio Grande do Sul and Santa Catarina, Brazil (Silva et al., 2016b). For this, incubation curves with dolomitic limestone rates of 0, 1.5, 3.0, and 6.0 Mg $ha^{-1}$ were used for both soils during incubation times of 7, 14, 21, 28, and 35 days. For LVdf and LVd, pH 5.5 was reached at 21 and 35 days at a rate of 3.0 Mg $ha^{-1}$ dolomitic limestone, respectively, which can be attributed to their different clay concentrations and buffering power. The soils were kept moist, with 60% of maximum water-holding capacity to allow of the reaction of limestone. The maximum water-holding capacity of the soils was determined according to Teixeira et al. (2017).

For basal fertilization, N, K, S, B, Cu, Fe, Mn, and Zn were applied, respectively, as 150 mg $NH_4NO_3$, 150 mg $KNO_3$, 50 mg $(NH_4)_2SO_4$, 1.0 mg $H_3BO_3$, 1.5 mg $CuCl_2$, 5.0 mg $FeSO_4.7H_2O$-EDTA, 4.0 mg $MnCl_2$. $H_2O$, and 5.0 mg $ZnCl_2$ per kilogram of soil.

Phosphate fertilization was based on the remaining P and applied to the total volume of the soils (Table 1). The used P sources contained $(NH_4)H_2PO_4$ and $KH_2PO_4$ at a rate of 450 mg $kg^{-1}$ for both soils. The soil samples were incubated again for 15 days, with moisture maintained at 60% of maximum water-holding capacity. Nitrogen, as urea, was applied four times every 15 days, starting on the fifteenth day after the seedlings were transplanted, totalizing 110 mg $kg^{-1}$ urea.

After liming and fertilization, a soil sample was taken from each treatment (pot) for the chemical analysis (Teixeira et al., 2017). Because of the small amount of soil (3.0 kg), sampling was done by inserting a half-inch polyvinyl chloride pipe, with 0.40 m of length, into four holes drilled along the entire length of the pot.

After the soil was collected, the seedlings were washed with distilled water and transplanted with bare root. The plants were guided using an espalier with a smooth wire, at a height of 0.8 m from the base of the pot, without being trimmed but spread and attached with ribbons when necessary. Throughout the experimental period, the pots were irrigated daily with distilled water to maintain soil moisture at 60% of maximum water-holding capacity. Weed control was done manually.

Fruits were collected as soon as they presented a dark-red color, typical of ripe fruits, and, then, were weighed on analytical scales. Leaf sampling followed the recommendations for blackberries of Comissão de Química e Fertilidade do Solo (CQFS RS/SC) (Silva et al., 2016b). From each cultivar, leaf samples, consisting of sixth fully-expanded leaves, counted from the apex, including the petiole, were collected and, then, washed and dried in an oven with forced-air circulation, at 65°C, until reaching a constant mass. Afterwards, the leaves were ground and subjected to the chemical reaction analysis to determine nutrient concentrations (Silva, 2009).

The obtained data were subjected to the analysis of variance, with Tukey's test, at 1% probability, for cultivars and soil types, and to regression equations as a function of the liming rates applied to the soils, using the Sisvar, version 5.6, software (Ferreira, 2011). From these equations, the amount of limestone to obtain maximum fruit yield was estimated. Then, the optimum values for soil chemical attributes and nutrient foliar concentrations were determined by substituting, in the regression equations, liming rate x for the amount of limestone with which the maximum fruit yield was reached.

## Results and Discussion

A significant interaction was observed between blackberry cultivars and liming regarding fruit yield, without a significant difference between the studied soils. In the adjustment of the regression equations for fruit yield as a function of the limestone rates applied to the soils, the quadratic model was the one that best fitted the data (Figure 2). From these equations, the fruit yield of each cultivar was estimated at a rate of 3.3 Mg $ha^{-1}$ limestone, the liming level that best expressed the productive potential of all cultivars in both soils (Table 2). This result can be explained by the decrease or elimination of toxic Al concentrations in the blackberry crop (Li et al., 2016) and the increase in Ca and Mg availability at this rate, improving soil cation balance and base saturation (Rietra et al., 2017), with a consequent increase in the fruit yield of all cultivars.

Without the application of limestone, the highest yield was observed for the BRS Tupy cultivar, followed by Brazos, BRS Xavante, and Guarani. However, all cultivars showed a similar response to the applied


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limestone rates, with a maximum fruit yield obtained with 3.3 Mg $ha^{-1}$ dolomitic limestone.

The higher yield of cultivar BRS Tupy can be attributed to its shorter flowering and harvesting period compared with those of the other evaluated cultivars (Curi et al., 2015; Oliveira et al., 2017). This difference in fruit yield can also be explained by genetic traits, such as fruit weight. The BRS Tupy cultivar presents, on average, fruits weighing from 8.0 to 10 g, followed by, in a decreasing order, Brazos, BRS Xavante, and Guarani, with 8.0, 6.0, and 5.0 g, respectively (Raseira & Frazon, 2012). A larger fruit size was also found for cultivar BRS Tupy in the municipalities of Lavras (Curi et al., 2015) and Pouso Alegre (Caproni et al., 2016), both in the state of Minas Gerais, Brazil.

In the literature, liming has been shown to be the most effective management practice to reduce soil acidity, consequently improving plant growth and yield (Bhat et al., 2010; Sikiric et al., 2011). This finding was observed for blackberry, in the present study, and also for other crops, such as raspberry (*Rubus idaeus* L.) (Sikiric et al., 2011) and physalis (Braga Neto et al., 2019).

Soil chemical attributes did not differ between the two soil types as a function of limestone rates (Table 2). The optimum values of each attribute were estimated from the limestone rates used to obtain the maximum fruit yield and regression equations (Figure 2). In relation to the soil chemical attributes prior to the experiment, liming increased pH value, Ca and Mg concentration, and their respective soil saturation and base saturation (Table 2). Similar results were found by Silva et al. (2016a) for physic nut and Braga Neto et al. (2019) for physalis. An increase in soil K was observed with liming, but with a decrease in the nutrient's availability, Al concentration, and their respective saturation (Table 1).

The average Al concentration dropped from 20.6 to 1.8 $mmol_c\ kg^{-1}$ (Table 1), resulting in a 91% decrease (Table 2), similar to that of 88.5% reported by Li et al. (2019). This represents a significant positive effect on soil pH, which becomes less acid due to liming, causing Al precipitation as $Al(OH)_3$ and decreasing free Al in the soil and, consequently, Al saturation (Fontoura et al., 2019; Holland et al., 2019).

The average Ca and Mg concentrations were 0.95 and 0.8 $mmol_c\ kg^{-1}$, increasing to 33.5 and 11.8 $mmol_c\ kg^{-1}$, respectively, which represent increases of 3.426 and 1.375%, leading to an increase in soil base saturation. The increase in exchangeable Ca and Mg concentrations in the soil after the addition of limestone was also reported by Silva et al. (2016a), Li et al. (2019), Braga Neto et al. (2019), and Fontoura et al. (2019).

The interaction between K, Ca, and Mg has been previously described by Silva & Trevizam (2015), who highlighted that Ca and Mg are bivalent cations,

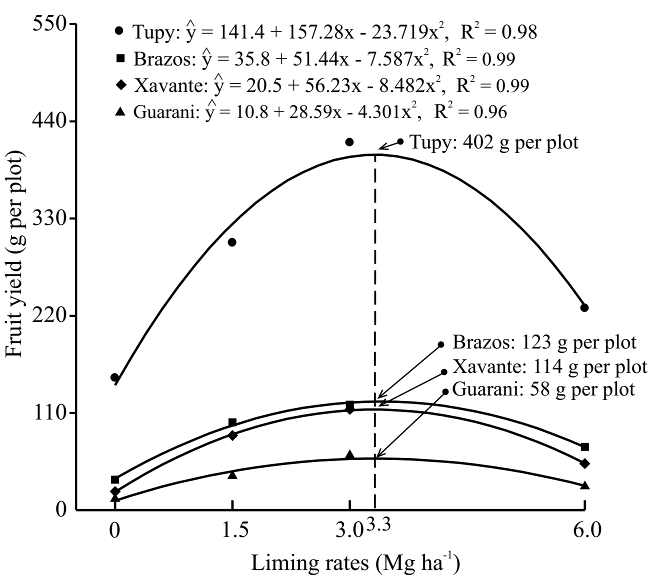


**Figure 2.** Fruit yield of the BRS Tupy, Brazos, BRS Xavante, and Guarani blackberry (*Rubus* spp.) cultivars as a function of liming rates.

**Table 2.** Regression equations and coefficients of determination ($R^2$) for soil chemical attributes ($\hat{y}$) as a function of liming rates (x) and optimal values for maximum fruit yield of blackberry (*Rubus* spp.) cultivars.

| Chemical attribute | Regression equation | $R^2$ | F-test | Value |
|---|---|---|---|---|
| $pH_{water}$ | $\hat{y} = 4.2 + 0.7909x^{0.5}$ | 0.95 | 32.7** | 5.6 |
| K ($mmol_c\ kg^{-1}$) | $\hat{y} = 5.1 - 0.2631x^{0.5}$ | 0.94 | 14.2** | 4.6 |
| Ca ($mmol_c\ kg^{-1}$) | $\hat{y} = 0.4 + 18.2171x^{0.5}$ | 0.99 | 168.6** | 33.5 |
| Mg ($mmol_c\ kg^{-1}$) | $\hat{y} = 0.1 + 6.4196x^{0.5}$ | 0.97 | 321.3** | 11.8 |
| Al ($mmol_c\ kg^{-1}$) | $\hat{y} = 17.6 - 8.6808x^{0.5}$ | 0.83 | 330.4** | 1.8 |
| Al saturation (%) | $\hat{y} = 63.2 - 31.5071x^{0.5}$ | 0.82 | 152.3** | 6.0 |
| Base saturation (%) | $\hat{y} = 5.3 + 23.6641x^{0.5}$ | 0.99 | 78.6** | 48.3 |
| Ca saturation (%) | $\hat{y} = 0.4 + 17.6871x^{0.5}$ | 0.99 | 77.5** | 32.5 |
| Mg saturation (%) | $\hat{y} = 0.1 + 6.2326x^{0.5}$ | 0.97 | 79.8** | 11.4 |
| K saturation (%) | $\hat{y} = 4.9 - 0.2554x^{0.5}$ | 0.97 | 20.2** | 4.4 |

**Significant at 1% probability. x = 3.3 Mg $ha^{-1}$.

although Ca is less hydrated than Mg and, therefore, more strongly retained by soil colloids, whereas K is monovalent and retained with less strength, i.e., $Ca^{2+} > Mg^{2+} > K^{+}$. For this reason, when limestone is applied, soil acidity is neutralized and acid cations are replaced by Ca and Mg in the soil, displacing $K^{+}$ from cation exchange sites (Damaceno et al., 2020). These factors may explain the effects of liming on K reduction and saturation in the soil, as well as the increase in the concentrations of Ca and Mg and in their respective saturations (Table 2).

Regarding soil pH, blackberries, in general, are tolerant to a wide range from 4.5 to 7.5, which allows them to be grown in different soil types (Strik & Finn, 2012). Hall & Funt (2017) found that blackberry shows a very good performance within a pH range from 5.6 to 6.8. After liming application, the optimum pH was 5.8 for raspberry (Sikiric et al., 2011) and 5.6 for blackberry (Table 2), a value close to that of 5.5 recommended by Comissão de Química e Fertilidade do Solo – RS/SC (Silva et al., 2016b).

The ideal base saturation for the blackberry crop was 48.3% after liming (Table 2), which neutralizes exchangeable Al, increasing base saturation (Damaceno et al., 2020). For physic nut and physalis, Silva et al. (2016a) and Braga Neto et al. (2019) found that the base saturation for maximum plant growth after liming was 52 and 67%, respectively. As a direct measure, base saturation can indicate the behavior and availability of nutrients in the soil, being a general indicator of its quality, considered even better than others such as pH value (Bieganowski et al., 2013; Kobierski et al., 2015). Therefore, knowledge of the optimal liming rates to correct acidity problems and improve soil fertilization conditions for blackberry cultivation is essential, allowing to reach an increased yield in different soils (Silva et al., 2016a).

There was an interaction between the nutrient concentrations in the leaves of the blackberry cultivars as a function of liming rates. For the fitted regression equations, the linear and square root models showed the best fit for the concentrations of macro- and micronutrients in the leaves, respectively (Table 3). Regarding the macronutrients, the concentrations of P, Ca, Mg, and S increased after the application of the limestone rates, while those of N and K decreased. However, all micronutrients showed a reduced concentration with increasing limestone rates.

The adequate nutrient concentrations in the leaves of each blackberry cultivar were estimated at the applied lime rate of 3.3 Mg $ha^{-1}$, with equations adjusted for nutrient concentration as a function of the applied limestone rates (Table 3). In general, the highest concentrations of nutrients to reach maximum fruit yield were observed in the leaves of cultivar BRS Tupy, followed by Brazos, BRS Xavante, and Guarani.

After the application of limestone, due to the greater dilution of N in the leaves, the concentration of this nutrient decreased more than that of K (Table 3), explaining why it is the most absorbed by blackberry (Hall & Funt, 2017). The N concentration found for cultivars BRS Tupy, BRS Xavante, and Guarani was higher than the critical level of 25.5 g $kg^{-1}$ determined by Gaurat et al. (2023) for blackberry. Regarding K, the obtained concentration was lower than the critical level of 11.2 g $kg^{-1}$ recommended by these authors for the crop. Similarly, Sikiric et al. (2011) also reported that K content decreased after different liming rates in raspberry.

These results are an indicative of the importance of liming to increase nutrient availability, particularly of Ca and Mg (Braga Neto et al., 2019). At high concentrations, Ca increases the uptake of cations and anions, as a synergistic effect, due to its role in maintaining plasma membrane integrity (Silva & Trevizam, 2015).

Since blackberries have a relatively low P requirement (Hall & Funt, 2017), the concentration of this nutrient was higher than the critical level of 2.0 g $kg^{-1}$ recommended for blackberry (Gaurat et al., 2023) in all evaluated cultivars, except Brazos, which showed the second best fruit yield (Figure 2).

Regarding the other macronutrients in the studied cultivars, the concentrations of Ca, Mg, and S were higher than the critical levels of 2.9, 2.9 and 0.6 g $kg^{-1}$, respectively, determined for blackberry (Gaurat et al., 2023).

The concentration of all cationic micronutrients was reduced with the increase in soil pH (Table 3). Barrow & Hartemink (2023) confirmed that, in a soil with a high calcium carbonate ($CaCO_3$) content, the availability of micronutrients is reduced due to a high soil pH, where hydroxyl ($OH^{-}$) reacts with $Fe^{3+}$, $Zn^{2+}$, and $Cu^{2+}$ and decreases the solubility product of the nutrient, forming ionic complexes such as $Fe(OH)_3$ and $Zn(OH)_2$. However, the concentrations of Cu, Mn,

**Table 3.** Nutrient concentrations in leaves of blackberry (*Rubus* spp.) cultivars for each applied liming rate and resulting regression equations (ŷ) as a function of liming rates (x), coefficients of determination ($R^2$), and adequate concentration (CA) for maximum fruit yield.

| Nutrient | Cultivar | Liming rate ($Mg\ ha^{-1}$) | | | | Regression equation | $R^2$ | F-test | CA |
|---|---|---|---|---|---|---|---|---|---|
| | | 0 | 1.5 | 3.0 | 6.0 | | | | |
| | | Macronutrient in leaves ($g\ kg^{-1}$) | | | | | | | |
| N | BRS Tupy | 29.8 | 28.7 | 27.6 | 20.7 | $\hat{y} = 30.7 - 1.5323x$ | 0.92 | 6.5** | 25.7 |
| | Brazos | 26.9 | 24.6 | 23.9 | 23.1 | $\hat{y} = 26.1 - 0.5784x$ | 0.81 | 5.0** | 24.2 |
| | BRS Xavante | 35.4 | 29.7 | 29.3 | 19.1 | $\hat{y} = 35.2 - 2.5847x$ | 0.95 | 17.3** | 26.6 |
| | Guarani | 35.5 | 27.9 | 26.5 | 23.8 | $\hat{y} = 33.0 - 1.7456x$ | 0.80 | 9.5** | 27.2 |
| P | BRS Tupy | 2.4 | 3.2 | 3.9 | 5.3 | $\hat{y} = 2.4 + 0.4704x$ | 0.99 | 13.5** | 4.0 |
| | Brazos | 1.0 | 1.2 | 1.9 | 2.7 | $\hat{y} = 0.9 + 0.2945x$ | 0.98 | 5.4** | 1.9 |
| | BRS Xavante | 1.1 | 1.8 | 2.3 | 4.2 | $\hat{y} = 1.0 + 0.5151x$ | 0.98 | 16.4** | 2.7 |
| | Guarani | 1.2 | 1.6 | 2.5 | 3.7 | $\hat{y} = 1.2 + 0.4268x$ | 0.98 | 11.2** | 2.6 |
| K | BRS Tupy | 9.7 | 8.5 | 7.6 | 5.2 | $\hat{y} = 9.7 - 0.7486x$ | 0.99 | 23.3** | 7.3 |
| | Brazos | 8.6 | 9.1 | 9.1 | 6.4 | $\hat{y} = 9.4 - 0.4037x$ | 0.90 | 10.8** | 8.0 |
| | BRS Xavante | 12.7 | 10.5 | 11.7 | 7.0 | $\hat{y} = 12.7 - 0.8692x$ | 0.81 | 388** | 9.9 |
| | Guarani | 9.9 | 8.4 | 8.2 | 7.2 | $\hat{y} = 9.5 - 0.4071x$ | 0.90 | 7.7** | 8.2 |
| Ca | BRS Tupy | 4.9 | 7.0 | 9.1 | 13.2 | $\hat{y} = 5.0 + 1.369x$ | 0.99 | 30.4** | 9.5 |
| | Brazos | 4.4 | 6.4 | 7.8 | 11.2 | $\hat{y} = 4.5 + 1.1200x$ | 0.99 | 20.3** | 8.2 |
| | BRS Xavante | 3.7 | 4.5 | 5.0 | 7.9 | $\hat{y} = 3.4 + 0.7081x$ | 0.96 | 8.5** | 5.8 |
| | Guarani | 3.9 | 4.4 | 5.3 | 6.6 | $\hat{y} = 3.8 + 0.4714x$ | 0.99 | 5.2** | 5.3 |
| Mg | BRS Tupy | 3.3 | 3.8 | 4.2 | 4.9 | $\hat{y} = 3.3 + 0.2715x$ | 0.99 | 8.1** | 4.2 |
| | Brazos | 2.4 | 3.3 | 3.9 | 5.3 | $\hat{y} = 2.5 + 0.4679x$ | 0.99 | 24.0** | 4.0 |
| | BRS Xavante | 3.7 | 3.9 | 4.1 | 4.9 | $\hat{y} = 3.6 + 0.1951x$ | 0.97 | 4.3** | 4.3 |
| | Guarani | 3.0 | 3.2 | 3.4 | 3.8 | $\hat{y} = 3.0 + 0.1442x$ | 0.99 | 7.2** | 3.4 |
| S | BRS Tupy | 1.1 | 1.1 | 1.3 | 1.4 | $\hat{y} = 1.1 + 0.064$ | 0.99 | 16.8** | 1.3 |
| | Brazos | 1.1 | 1.6 | 1.9 | 2.8 | $\hat{y} = 1.1 + 0.2813x$ | 0.99 | 18.1** | 2.0 |
| | BRS Xavante | 0.8 | 1.4 | 1.5 | 2.8 | $\hat{y} = 0.8 + 0.3173x$ | 0.97 | 23.7** | 1.8 |
| | Guarani | 0.7 | 1.2 | 1.6 | 2.6 | $\hat{y} = 0.7 + 0.3039x$ | 0.99 | 21.1** | 1.7 |
| | | Micronutrient in leaves ($mg\ kg^{-1}$) | | | | | | | |
| B | BRS Tupy | 149.7 | 128.5 | 118.8 | 86.1 | $\hat{y} = 154.1 - 24.703x^{0.5}$ | 0.93 | 18.8** | 109.3 |
| | Brazos | 130.2 | 105.8 | 92.9 | 53.8 | $\hat{y} = 135.8 - 29.7338x^{0.5}$ | 0.92 | 27.3** | 81.8 |
| | BRS Xavante | 27.7 | 19.1 | 11.4 | 4.3 | $\hat{y} = 28.6 - 9.6201x^{0.5}$ | 0.98 | 12.7** | 11.1 |
| | Guarani | 57.0 | 51.4 | 44.5 | 31.9 | $\hat{y} = 59.6 - 9.892x^{0.5}$ | 0.90 | 13.1** | 41.6 |
| Cu | BRS Tupy | 48.2 | 23.6 | 16.8 | 9.7 | $\hat{y} = 46.2 – 16.0239x^{0.5}$ | 0.97 | 47.6** | 17.1 |
| | Brazos | 22.0 | 16.7 | 14.2 | 11.9 | $\hat{y} = 21.9 – 4.2029x^{0.5}$ | 0.99 | 23.1** | 14.3 |
| | BRS Xavante | 28.1 | 21.7 | 10.7 | 4.8 | $\hat{y} = 29.6 – 9.8434x^{0.5}$ | 0.93 | 18.7** | 11.7 |
| | Guarani | 18.9 | 14.8 | 9.8 | 2.7 | $\hat{y} = 20.3 – 6.5037x^{0.5}$ | 0.92 | 28.3** | 8.5 |
| Fe | BRS Tupy | 222.1 | 189.9 | 148.6 | 103.3 | $\hat{y} = 231.3 – 48.3563x^{0.5}$ | 0.94 | 21.3** | 143.5 |
| | Brazos | 290.1 | 266.4 | 207.9 | 192.3 | $\hat{y} = 296.6 – 42.4974x^{0.5}$ | 0.88 | 17.4** | 219.4 |
| | BRS Xavante | 173.8 | 129.0 | 83.2 | 52.1 | $\hat{y} = 178.3 – 50.8853x^{0.5}$ | 0.97 | 22.7** | 85.9 |
| | Guarani | 204.7 | 129.9 | 117.6 | 96.3 | $\hat{y} = 197.5 – 44.6745x^{0.5}$ | 0.96 | 17.8** | 116.3 |
| Mn | BRS Tupy | 417.1 | 329.4 | 283.6 | 197.1 | $\hat{y} = 425.9 – 88.0977x^{0.5}$ | 0.98 | 13.7** | 265.8 |
| | Brazos | 445.3 | 350.7 | 208.8 | 162.3 | $\hat{y} = 456.3 – 121.7265x^{0.5}$ | 0.93 | 17.5** | 235.1 |
| | BRS Xavante | 444.0 | 245.4 | 186.2 | 118.4 | $\hat{y} = 430.7 – 134.8056x^{0.5}$ | 0.98 | 18.7** | 185.8 |
| | Guarani | 727.2 | 256.6 | 141.8 | 112.8 | $\hat{y} = 664.2 – 262.3393x^{0.5}$ | 0.90 | 23.4** | 187.6 |
| Zn | BRS Tupy | 55.1 | 46.7 | 33.3 | 25.6 | $\hat{y} = 56.9 – 12.4133x^{0.5}$ | 0.94 | 19.4** | 34.4 |
| | Brazos | 41.9 | 35.6 | 25.3 | 14.9 | $\hat{y} = 44.3 – 11.0088x^{0.5}$ | 0.92 | 15.6** | 24.3 |
| | BRS Xavante | 51.1 | 50.5 | 30.8 | 25.5 | $\hat{y} = 54.6 – 11.2023x^{0.5}$ | 0.93 | 19.4** | 34.3 |
| | Guarani | 38.9 | 29.9 | 29.0 | 17.8 | $\hat{y} = 39.8 – 8.0857x^{0.5}$ | 0.93 | 18.1** | 25.1 |

**Significant at 1% probability. x = 3.3 $Mg\ ha^{-1}$.


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Zn, and Fe in the leaves of the evaluated blackberry cultivars were higher than the critical levels of 9.7, 116.4, 22.9 and 79.6 mg kg$^{-1}$, respectively, reported by Gaurat et al. (2023), which could be attributed to the greater need for nutrient absorption in response to liming since the critical levels in the present study were calculated for the maximum fruit yield of the cultivars.

The concentration of Mn was higher than the critical level determined for the blackberry crop and was the highest among micronutrients in the leaves of all cultivars (Table 3). A similar result was found for Allegheny blackberry (*Rubus allegheniensis* Porter), which accumulates high concentrations of Mn in its leaves (Gilliam et al., 2018). Even though there was a reduction in B concentration as a function of the applied limestone rate, its critical level was higher than that of 15.5 mg kg$^{-1}$ for blackberry.

In the diagnostic leaf of blackberry, the adequate concentrations of macronutrients were 25, 3.3, 9.9, 13.8, 4.2, and 2.6 g kg$^{-1}$ N, P, K, Ca, Mg, and S, respectively, whereas those of micronutrients were 62.5, 203, 31.2 and, 30.2 mg kg$^{-1}$ B, Fe, Mn, and Zn. To achieve the maximum fruit yield in all cultivars, the adequate concentrations of the macronutrients were 25.9, 2.8, 8.4, 7.2, 4.0, and 1.7 g kg$^{-1}$ N, P, K, Ca, Mg, and S, respectively, and those of the micronutrients were 61, 12.9, 141.3, 218.6, and 29.5 mg kg$^{-1}$ B, Cu, Fe, Mn, and Zn.

Considering the obtained results, the maximum yield potential of the blackberry cultivars cultivated in the evaluated soils was reached with pH ($H_2O$) 5.6, maximum aluminum saturation tolerated of 6%, Ca and Mg concentration of 45.3 mmolc kg$^{-1}$, and base saturation of 48.3%.

The findings related to the adequate concentration of nutrients in the leaves and the mean adequate nutrient concentrations for maximum fruit yield of all studied blackberry cultivars are of great relevance as they could reduce the occurrence of inadequate diagnoses of nutrient deficiencies, excesses, or imbalances, consequently increasing yield with soil correction.

Therefore, considering the lack of studies to define the adequate soil acidity levels to calculate liming requirements for blackberry, especially in subtropical climate regions, the results observed in the present work will contribute for the implantation and management of blackberry fertilization before compromising yield.

## Conclusion

The maximum fruit yield of blackberry (*Rubus* spp.) grown in acidic soils is obtained at pH 5.6, maximum tolerated aluminum saturation of 6%, calcium and magnesium concentration of 45.3 $mmol_c$ kg$^{-1}$, and base saturation of 48.3% with the application of 3.3 Mg ha$^{-1}$ dolomitic limestone.

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