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Gypsum Recommendations for Sandy Soil Cultivated with Soybean

Recomendação de Gesso em Solo Arenoso Cultivado com Soja

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Abstract

Liming aims to neutralize phytotoxic Al^{3+} and H^+. However, its effects are limited to the surface layers of soil. Gypsum is a complementary agricultural input whose application is recommended by different methods, with rates varying greatly. The purpose of this study was to assess the effect of different gypsum rates, alone or in combination with lime, on soybean development and chemical properties of a typical dystrophic Red-Yellow Latosol with sandy texture. PVC columns filled with soil were used for the experiment. Treatments consisted of eight gypsum rates (0, 321, 592, 619, 710, 887, 4198, and 4308 kg ha^{-1}) combined or not with lime application. Seeds of soybean M6410 RR2 PRO® were sown, and vegetative attributes and soil chemical properties were evaluated after 128 days. A gypsum rate of 2239 kg ha^{-1} combined with liming provided the maximum technical efficiency for vegetative attributes and can be used as a reference value for soybean cultivation in sandy Latosols. Liming was efficient in increasing plant height, stem diameter, dry matter accumulation, pod number, grain number, and grain yield. Base saturation, exchangeable calcium, Ca^{2+} saturation, and available sulfur can be used as criteria for gypsum application to sandy Latosols.

Keywords: Productive Efficiency. Sulfur. Yield. Liming. Gypsum Application.

Resumo

A calagem visa a neutralização de Al^{3+} e H^+ fitotóxicos, entretanto é limitada às camadas superficiais do solo. O gesso é insumo complementar cuja aplicação é recomendada por diferentes métodos, com doses variando amplamente. Assim, objetivou-se avaliar métodos de gessagem combinados ou não à calagem, sobre o desenvolvimento de soja e atributos químicos de um Latossolo Vermelho-Amarelo Distrófico típico arenoso. Foram utilizadas colunas de PVC preenchidas com o solo, sendo os tratamentos constituídos por oito doses de gesso (0; 321, 592; 619; 710; 887, 4.198 e 4.308 kg ha^{-1}) combinados ou não à calagem. Semeou-se soja, cultivar M6410 RR2 PRO® e após 128 dias, foram avaliados atributos vegetativos e parâmetros químicos do solo. A dose de gesso de 2.239 kg ha^{-1} associada à calagem resultou na máxima eficiência técnica para atributos de planta e pode ser referência no cultivo de soja em Latossolo arenoso. A calagem foi eficiente no aumento da altura de plantas, diâmetro de caule, acúmulo de massa seca, número de vagens, número de grãos e na produtividade. A saturação por bases, o cálcio trocável, a saturação de Ca^{2+} na CTCe e o enxofre disponível podem ser usados como critérios de gessagem em Latossolos arenosos.

Palavras-chave: *Eficiência Produtiva. Enxofre. Rendimento. Calagem. Gessagem.*

1 Introduction

Soybean, a prevalent oilseed crop in Brazil, witnessed a staggering production of 118 million tonnes in the 2017/2018 season across approximately 35.1 million hectares, constituting 57% of the nation's total grain cultivation area (CONAB, 2018). While these figures reflect significant success, research underscores the potential for substantially elevating soybean yields. Addressing soil acidity in no-till mulch-based systems emerges as a critical step not only to boost soybean production but also to secure the sustainability and economic feasibility of agricultural endeavors.

The sensitivity of soybeans to soil acidity poses a crucial challenge, hindering the development of the plant's deep root system. Left unchecked, this acidity curtails nutrient and water uptake, particularly during dry spells, ultimately compromising crop yields (AGRAHARI et al., 2020).

Among the prevalent practices, liming stands out as a widely embraced technique in crop cultivation. Beyond its role in neutralizing soil acidity, liming supplements plants with accessible calcium (Ca) and magnesium (Mg) while mitigating or eradicating Al^{3+} toxicity (COSTA et al., 2015; DUARTE et al., 2021; COSTA et al., 2022). However, its efficacy in no-till systems remains confined to the surface layers (0–10 cm), leading to dwindling Ca and Mg availability in deeper soil levels over time (TOMELERO et al., 2016).

Agricultural gypsum emerges as a promising solution, being significantly more soluble than lime. This compound not only provides calcium but also sulfur to the soil solution (RAMOS et al., 2006; VITTI et al., 2015). An additional benefit is the reduction in aluminum saturation due to the formation of non-toxic ionic pairs (VITTI AND PRIORI, 2009), making gypsum application an attractive strategy for improving deeper soil layers and enhancing root environments

(NEIS et al., 2010).

Guidelines for gypsum application hinge on various soil criteria, including aluminum and calcium content thresholds across specific soil layers in distinct regions of Brazil (LOPES; GUIMARÃES, 1989; RAIJ et al., 1997; SOUSA et al., 1992). However, the existing equations for calculating gypsum rates exhibit discrepancies owing to diverse soil textures, warranting further investigations, especially for sandy soils, which inherently lack nutrients and thus limit plant growth. Harmonizing gypsum application rates in accordance with soil properties and regional nuances holds promise in optimizing soil conditions and augmenting crop yields sustainably. In view of the above, this study aimed to investigate the effect of different gypsum rates, applied alone or in combination with lime, to establish the optimal amendment strategy for soybean cultivation in a typical dystrophic Red-Yellow Latosol with sandy texture.

2 Material and Methods

This study was conducted in an experimental area (23°47′27.38″S 53°15′25.58″W, 406 m a.s.l.) at the State University of Maringá (UEM), Umuarama, Paraná, Brazil. The climate is subtropical with hot summers (Cfa type in the Köppen classification). Annual average temperatures vary from 20 to 22 °C, and the annual rainfall ranges from 1300 to 1600 mm (ALVARES et al., 2013). The soil is a typical dystrophic Red-Yellow Latosol with sandy texture (EMBRAPA, 2013). Soil samples were collected in August 2017 for analysis of chemical and physical properties (Table 1).

Table 1 – Chemical and granulometric properties in the 0–20 cm layer of a typical dystrophic Red-Yellow Latosol with sandy texture collected at the experimental site in Umuarama campus, State University of Maringá (CAU/UEM), Paraná, Brazil, 2017

pH (H_2O)	Al^{3+}	Ca^{2+}	Mg^{2+}	CEC	K^+	P	S	OM	BS	AS	Clay	Sand	Silt
	--------- $cmol_c\ dm^{-3}$ ---------				----- $mg\ dm^{-3}$ -----			$g\ dm^{-3}$	----- % -----		--------- $g\ kg^{-1}$ ---------		
4.63	1.25	0.85	0.38	5.69	11.7	4.72	4.38	8.57	22.14	49.80	11.83	82.72	5.45

Al^{3+}, Ca^{2+}, and Mg^{2+} were extracted with 1 mol L^{-1} KCl. P and K^+ were extracted with Mehlich-1 reagent (0.05 mol L^{-1} HCl + 0.025 mol L^{-1} H_2SO_4). S was extracted with ammonium acetate and acetic acid solution. CEC, cation-exchange capacity at pH 7.0; OM, organic matter; BS, base saturation; AS, aluminum saturation.

Source: research data.

According to the classification of soil parameters described in the Fertilization and Liming Manual of Paraná State (PAULETTI; MOTTA, 2017), the topsoil (0–20 cm layer) used in the study had very low pH (pH $H_2O < 4.7$), intermediate content of exchangeable aluminum (Al^{3+} level between 0.8 and 1.5 $cmol_c\ dm^{-3}$), low calcium (Ca^{2+} level between 0.5 and 1.0 $cmol_c\ dm^{-3}$) and magnesium (Mg^{2+} level between 0.2 and 0.38 $cmol_c\ dm^{-3}$) contents, very low potassium ($K^+ < 0.06\ cmol_c\ dm^{-3}$) and available phosphorus ($P < 6\ mg\ dm^{-3}$) contents, high sulfur content (SO_4^{2-}-S level between 3.1 and 6.0 mg dm^{-3}), low base saturation (21–35%), high Al^{3+} saturation (21–50%), low CEC at pH 7.0 (5–7 $cmol_c\ dm^{-3}$), and low clay content (<250 g kg^{-1}).

The design was a randomized block with an 8 × 2 factorial arrangement, totaling 16 treatments in 4 replications. Experimental units consisted of PVC columns measuring 150 mm in diameter and 0.5 m in height arranged in rows (blocks) spaced 0.5 m apart. Each column was kept in vertical position and filled with sandy Latosol. Treatments consisted of eight gypsum rates (0, 321, 592, 619, 710, 887, 4198, and 4308 kg ha^{-1}) combined or not with a fixed rate of dolomitic limestone (2476 kg ha^{-1}) with a relative power of total neutralization of 87%. Gypsum rates were calculated using methods consolidated in Brazil for determination of gypsum requirements (Table 2). The lime rate was calculated to raise base saturation to 60%, which is the reference value recommended for soybean crops (RAIJ et al., 1997; PAULETTI; MOTTA, 2017).

Table 2 – Methods for estimating gypsum requirements (GR) and calculated gypsum rates

Criteria	Equation for GR calculation	Gypsum rate (kg ha^{-1})
Soil texture (clay content)[1]	GR (t ha^{-1}) = $0.00034 - 0.002445x^{0.5} + 0.0338886x - 0.00176366x^{1.5}$	321
Clay content – Cerrado I[2]	GR (kg ha^{-1}) = 50 × Clay percentage	592
Subsurface correction[3]	GR (kg ha^{-1}) = 0.25 × Lime requirement	619
Clay content – São Paulo[4]	GR (kg ha^{-1}) = 60 × Clay percentage	710
Clay content – Cerrado II[2]	GR (kg ha^{-1}) = 75 × Clay percentage	887
Ca contribution (%) to effective cation exchange-capacity (ECEC)[5]	GR (t ha^{-1}) = (0.6 × ECEC – Ca content in $cmol_c\ dm^{-3}$) × 6.4	4198
Cation-exchange capacity (CEC) and base saturation (BS)[3]	GR (t ha^{-1}) = ($BS_2 - BS_1$) × CEC ÷ 50* (or 500**)	4308

* For CEC expressed in $cmol_c\ dm^{-3}$. ** For CEC expressed in $mmol_c\ dm^{-3}$.

Source: Alvarez et al. (1999). Sousa et al. (1995). Vitti et al. (2008). Raij et al. (1997). Caires and Guimarães (2016).

Columns were placed in an area enclosed with wire fencing. Subsequently, six seeds of soybean M6410 RR2 PRO® were sown in each experimental unit. The soybean variety is transgenic, expressing genes that confer resistance to the herbicide glyphosate and some defoliating caterpillars.

Before planting, seeds were treated with fungicide, insecticide, bacterial inoculant, and micronutrients. At the VC stage, seedlings were thinned to two per experimental unit. Phosphorus and potassium fertilizers were applied at the time of sowing at a depth of 3 cm and close to the seeds at doses equivalent to 120 kg ha^{-1} P_2O_5 and 120 kg ha^{-1} K_2O, as per the recommendations of the Fertilization and Liming Manual of Paraná State (PAULETTI; MOTTA, 2017).

Disease management was performed 42 days after sowing, when plants reached the R3 stage (beginning of pod formation), by application of a fungicide product containing picoxystrobin + cyproconazole (Aproach® Prima, DuPont) at a spray volume equivalent to 0.3 L ha^{-1} commercial product + 0.75 L ha^{-1} adjuvant. For control of insect pests such as the brown stink bug (Euschistus heros) and the small green stink bug (Piezodorus guildinii), plants were treated at 68 days after sowing with imidacloprid + beta-cyfluthrin (Connect®, Bayer) at a spray volume equivalent to 1 L ha^{-1}.

At 128 days after germination, plants were cut at the base for collection of the aboveground material. Plant height was measured from the base of the plant (close to ground level) to the end of the main stem. Stem diameter was measured at 3 cm from the base of the main stem. Shoot dry weight was determined by oven-drying samples at 65 °C until constant weight was achieved. Number of pods per plant, number of grains per plant, and grain yield per plant were also determined.

At 130 days after installation of the experiment, the soil of PVC columns was sampled at a depth of 0–20 cm using a sand auger. Soil samples were air dried, sieved through 1.18 mm mesh sieves, and evaluated for pH H_2O (sample to solution ratio of 1:2.5), exchangeable aluminum (Al^{3+}, extracted with 1 mol L^{-1} KCl and determined by titration with 0.025 N NaOH solution containing 1% phenolphthalein indicator), exchangeable calcium and magnesium (Ca^{2+} and Mg^{2+}, extracted with 1 mol L^{-1} KCl and determined by atomic absorption spectrometry), exchangeable potassium (K^+, extracted with Mehlich-1, a solution consisting of 0.05 mol L^{-1} HCl and 0.025 mol L^{-1} H_2SO_4), and available sulfur (SO_4^{2-}-S, extracted with 0.05 mol L^{-1} HCl and determined by UV/Vis spectrophotometry). Potential acidity ($H^+ + Al^{3+}$) was estimated from the SMP index using the equation proposed by Sambatti et al. (2003): H + Al = 20.1925 – 2.6484 pH SMP, with R^2 = 0.91. Base saturation (BS) was calculated by the equation BS = 100 × SB/CEC, where SB is the sum of exchangeable base cations (Ca^{2+}, Mg^{2+}, and K^+) and CEC is the cation-exchange capacity at pH 7.0.

Crop and soil data were subjected to analysis of variance by the F-test ($p < 0.05$). As the factors gypsum rate and lime application were significant, data were also subjected to regression analysis. All statistical analyses were performed using SISVAR® software (FERREIRA, 2011).

3 Results and Discussion

3.1 Plant attributes

Different gypsum rates (G) significantly impacted plant height, stem diameter, shoot dry weight, pods, grains per plant, and yield ($p = 0.000$), while lime application (L) notably influenced most traits ($p < 0.05$). Their interaction (G × L) significantly affected all characteristics ($p = 0.000$). Coefficients of Variation (CV) ranged from 12.8% to 22.3%, highlighting trait variability.

When Gypsum application boosts soybean crop growth, this effect is attributed to increased calcium (Ca^{2+}) and sulfur (SO_4^{2-}-S) availability in subsurface layers, likely fostering root development (SOUZA et al., 2005). Additionally, it alleviated Al^{3+} toxicity (ALTERMAN, 2010; ZANDONÁ et al., 2015). However, high gypsum rates could compromise magnesium (Mg) and potassium (K) availability due to their leaching to deeper layers caused by sulfate anion (SO_4^{2-}) interactions with Mg^{2+} and K^+ cations (ZAMBROSI et al., 2007), potentially reducing topsoil Mg and K levels, thus hindering soybean yield.

Lime application, calculated via the base saturation method, notably influenced soybean development by enhancing Ca^{2+} and Mg^{2+} availability while reducing Al^{3+} toxicity (RODRIGUES et al., 2017). The interaction between gypsum rate and lime application significantly affected vegetative parameters. Lower gypsum rates combined with lime showed a positive impact on plant height, likely by increasing Ca^{2+} and Mg^{2+} availability (RODRIGUES et al., 2017). However, excessive gypsum rates (>4 t ha^{-1}) alongside liming led to decreased plant height due to competitive inhibition, causing a reduction in Mg and K availability (MEDEIROS et al., 2008).

Soil amendment with lime associated with gypsum rates of up to 710 kg ha^{-1} increased stem diameter compared with no lime application. For a gypsum rate of 887 kg ha^{-1}, liming did not influence stem diameter, whereas, for gypsum rates above 4 t ha^{-1}, liming decreased this vegetative attribute, possibly because of nutrient imbalance (Table 3).

Table 3 – Interaction effects of Gypsum rate × Lime application on plant height, stem diameter, and shoot dry weight of soybean crops grown in a typical dystrophic Red-Yellow Latosol in Umuarama, Paraná, Brazil, 2017/2018

Lime Application	Gypsum rate (kg ha^{-1})*							
	0	321	592	619	710	887	4198	4308
	Plant height (cm)							
Unlimed	24.7 b	31.8 b	39.4 b	43.5 a	47.4 a	45.9 a	54.7 a	53.9 a
Limed	35.1 a	46.0 a	52.7 a	53.8 a	52.1 a	46.8 a	46.3 b	36.3 b
	Stem diameter (cm)							

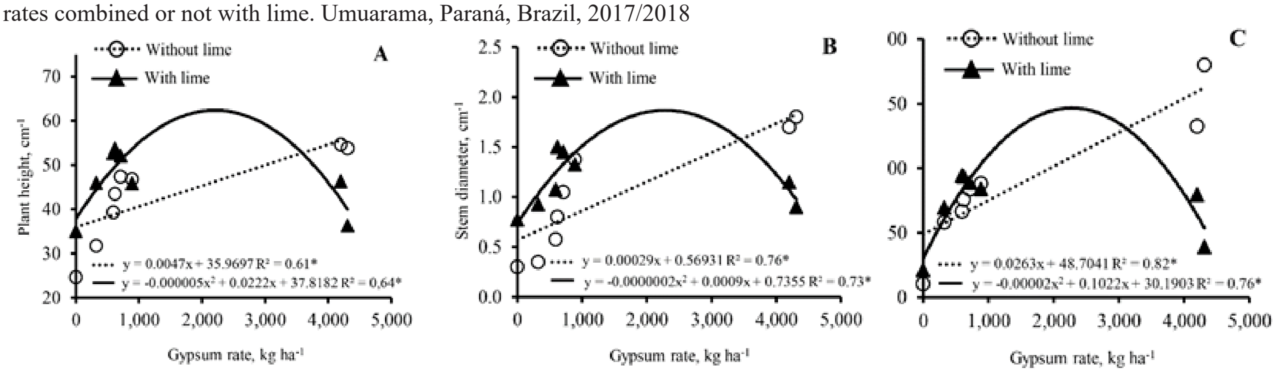
Lime Application	Gypsum rate (kg ha^{-1})*							
	0	321	592	619	710	887	4198	4308
Unlimed	0.30 b	0.35 b	0.58 b	0.80 b	1.05 b	1.38 a	1.70 a	1.80 a
Limed	0.78 a	0.93 a	1.08 a	1.50 a	1.45 a	1.33 a	1.15 b	0.90 b
	------------------------------------ Shoot dry weight (g) ------------------------------------							
Unlimed	10.5 a	58.4 a	66.6 b	75.4 a	83.8 a	88.3 a	132.6 a	180.3 a
Limed	21.2 a	69.7 a	94.6 a	93.7 a	88.9 a	84.0 a	79.6 b	38.9 b

Means within rows followed by different letters are significantly different by t-test (LSD, $p < 0.05$). * Significant at $p < 0.05$ by the F-test.
Source: research data.

Liming only significantly increased shoot dry weight when combined with 592 kg ha^{-1} gypsum. When liming was associated with gypsum rates of 4198 and 4308 kg ha^{-1}, there was a decrease in shoot dry weight of 40.0 and 78.4%, respectively. This reduction in dry matter accumulation in soybean shoots with the use of lime and high gypsum rates is probably due to nutritional imbalances caused by the lower availability of important elements for plant development, such as K and Mg, whose contents tend to decrease as a result of leaching to greater depths (CREMON et al., 2009; ZANDONÁ et al., 2015).

In untreated plots, soybean crop attributes showed a linear increase with rising gypsum rates (Figure 1), attributed to the elevation of exchangeable calcium (Ca^{2+}) and sulfur (SO_4^{2-}-S) contents from initial low levels (0.85 $cmol_c$ dm^{-3} Ca^{2+} and 4.38 mg dm^{-3} SO_4^{2-}-S), according to Paraná State's Fertilization and Liming Manual (PAULETTI; MOTTA, 2017). Sulfur's role in amino acid production and various plant growth processes is acknowledged (MODA et al., 2013). Gypsum's capability to diminish exchangeable aluminum (Al^{3+}) activity in deeper soil layers (VITTI; PRIORI, 2009) likely bolstered soybean development, evident in increased plant height, stem diameter, and shoot dry weight.

Figure 1 – (A) Plant height, (B) stem diameter, and (C) shoot dry weight of soybean crops grown in soil treated with different gypsum rates combined or not with lime. Umuarama, Paraná, Brazil, 2017/2018



Source: research data.

In the absence of lime, gypsum application boosted shoot dry weight and plant height compared to the control, with significant stem diameter increases only beyond 592 kg ha^{-1}. Gypsum induced pH elevation in subsurface layers through SO_4^{2-}-S leaching and ligand exchange with iron (Fe) and aluminum (Al) hydroxides, promoting pH elevation (CAIRES et al., 1999). This pH alteration neutralizes phytotoxic Al^{3+} (PROCHNOW; CANTARELLA, 2015), benefiting crop growth. In clayey Latosols treated with agricultural gypsum, Sousa et al. (2005) reported a 300 kg ha^{-1} yield increase in soybean crops.

The optimal gypsum rates for various soybean vegetative parameters were determined through an analysis (Figure 1). For plant height, the rate maximizing efficiency was 2176 kg ha^{-1}, projecting a height peak of 62.1 cm, differing from Bossolani's study (2018) where 2017 kg ha^{-1} reached 105.4 cm. Variations in cultivars can yield distinct responses to gypsum and lime application, impacting morphological traits.

Regarding stem diameter, the peak efficiency rate stood at 2045 kg ha^{-1}, estimating a maximum diameter of 1.84 cm. Pereira et al. (2016) found a mere 50 kg ha^{-1} elemental S application significantly increased stem diameter in soybean crops compared to the control. For dry biomass, the calculated peak efficiency rate was 2323 kg ha^{-1}, projecting a shoot dry weight of 149.04 g.

Notably, the optimal gypsum rates for soybean vegetative traits averaged approximately 48.05% and 49.37% lower than those recommended by Vitti et al. (2008) and Caires and Guimarães (2016), respectively. This suggests that using about half the recommended rate is optimal for sandy soils. High gypsum rates (>4 t ha^{-1}) in conjunction with lime (2476 kg ha^{-1}) reduced vegetative attributes, likely due to nutrient leaching to deeper soil layers, as highlighted by Ramos et al. (2013).

Recommendations based on base saturation, CEC, and Ca^{2+} saturation may not suit sandy soils due to their lower storage and buffering capacities, leading to nutrient imbalances (RESENDE et al., 2016). The interaction effects analysis (Table 4) showcased that 592 kg ha^{-1} gypsum combined with liming enhanced pod and grain numbers, boosting soybean yield. However, gypsum rates exceeding 4 t ha^{-1}, alongside lime, decreased grain yield due to altered cation proportions and availability in the soil solution. These findings stress the significance of balanced gypsum and lime application to optimize soybean production.

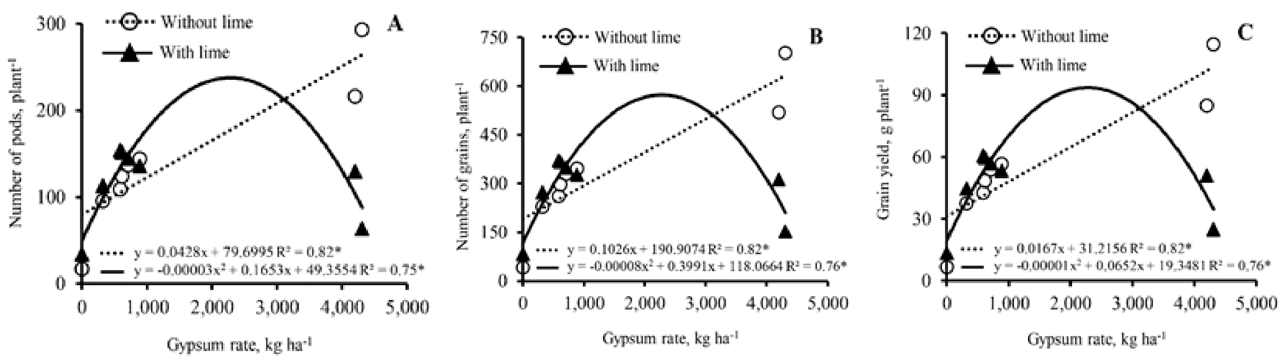
Table 4 – Interaction effects of Gypsum rate × Lime application on number of pods per plant, number of grains per plant, and yield of soybean crops grown in a typical dystrophic Red-Yellow Latosol in Umuarama, Paraná, Brazil, 2017/2018

Lime Application	Gypsum rate (kg ha^{-1})*							
	0	321	592	619	710	887	4198	4308
	------------------------------------ Pods plant^{-1} ------------------------------------							
Unlimed	17 a	96 a	109 b	124 a	137 a	144 a	216 a	294 a
Limed	35 a	114 a	154 a	152 a	145 a	136 a	130 b	64 b
	------------------------------------ Grains plant^{-1} ------------------------------------							
Unlimed	41 a	228 a	261 b	297 a	328 a	346 a	519 a	702 a
Limed	83 a	273 a	370 a	366 a	349 a	327 a	312 b	153 b
	------------------------------------ Yield (g plant^{-1}) ------------------------------------							
Unlimed	6.7 a	37.4 a	42.6 b	48.5 a	53.7 a	56.6 a	84.9 a	114.7 a
Limed	13.5 a	44.6 a	60.5 a	59.8 a	56.9 a	53.5 a	51.0 b	24.9 b

Means within rows followed by different letters are significantly different by t-test (LSD, $p < 0.05$). * Significant at $p < 0.05$ by the F-test.
Source: research data.

Gypsum application in unlimed soil showcased a positive linear correlation with soybean yield attributes, indicating higher rates led to increased productivity (Figure 2). Surface gypsum addition elevated Ca^{2+} content while reducing Al^{3+} saturation, enhancing root growth by limiting Al absorption (VITTI; PRIORI, 2009).

Figure 2 – (A) Number of pods per plant, (B) number of grains per plant, and (C) yield of soybean crops grown in soil treated with different gypsum rates combined or not with lime. Umuarama, Paraná, Brazil, 2017/2018



Source: research data.

However, combining gypsum with lime, particularly at rates exceeding 4 t ha^{-1}, diminished soybean potential. High gypsum rates might cause leaching of essential cations like K^{+} and Mg^{2+} to inaccessible soil layers, especially pronounced in sandy soils (CAIRES et al., 2004). Hence, recommendations by Vitti et al. (2008) and Caires and Guimarães (2016) might not suit sandy soils due to greater cation leaching.

The optimal gypsum rate for pod number, estimated at 2296 kg ha^{-1}, represents around half of the rates suggested by prior studies, indicating an optimum for sandy soil soybean cultivation. This treatment likely achieved a nutrient balance, promoting increased pod numbers by improving the root environment through enhanced nutrient availability and reduced phytotoxic elements (CAIRES et al., 2011 SORATTO; CRUSCIOL, 2008).

The maximum technical efficiency for grain number (570 grains) was achieved with 2267 kg ha^{-1} gypsum (Figure 2B), while the maximum efficiency for grain yield (92.3 g plant^{-1}) was estimated at 2329 kg ha^{-1} gypsum (Figure 2C). Without liming, this yield would demand 3635 kg ha^{-1} gypsum, emphasizing the economic advantage of combining lime with 2329 kg ha^{-1} gypsum, saving 1306 kg ha^{-1} gypsum. Considering 2018 cost estimates, this reduction translates to R$264.10, covering 82.05% of the total lime cost (R$321.88). Lime's added benefits include reducing Al toxicity and increasing base saturation to recommended levels for soybeans (60%). Moreover, lime naturally provides Mg^{2+}, absent in gypsum, enhancing root growth depth and plant development.

The mean gypsum rate achieving maximum technical efficiency for soybean yield and components when combined with lime was 2239 kg ha^{-1} (Table 5). This rate likely improved both surface and subsurface soil chemistry, particularly suitable for sandy Latosols. It stands 72.05% above recommendations based on soil texture and liming (ALVAREZ et al., 1999; RAIJ et al., 1997; SOUSA et al., 1995; VITTI et al., 2008) yet 52.65% lower than those based on base saturation, CEC, and Ca^{2+} saturation (CAIRES; GUIMARÃES, 2016; VITTI et al., 2008).

Table 5 – Gypsum rates of maximum technical efficiency for soybean crops grown in a typical dystrophic Red-Yellow Latosol with sandy texture treated with lime in Umuarama, Paraná, Brazil, 2017/2018

Variable	Optimum gypsum rate (kg ha^{-1})
Plant height	2,176
Stem diameter	2,045
Shoot dry weight	2,323
Number of pods per plant	2,296
Number of grains per plant	2,267
Yield per plant	2,329
Mean gypsum rate (kg ha^{-1})	**2,239**
Standard deviation (kg ha^{-1})	110.3
Coefficient of variation (%)	4.9

Source: research data.

These findings demonstrate that the gypsum rates obtained by current methods of estimation may not be suitable for soybean grown in sandy soils. The current recommended rates are either insufficient or economically unfeasible, as they do not afford maximum gains in vegetative attributes.

3.2 Soil chemical properties

The F-test results underscored the substantial impact of both Gypsum rate (G) and Lime application (L) on various soil attributes. Gypsum rate notably impacted Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, and SO_4^{2-}-S levels, alongside Ca^{2+} and Mg^{2+} saturation ($p = 0.000$). Lime application similarly influenced various parameters, including Al^{3+}, pH, and base saturation ($p = 0.000$). Their interaction (G × L) significantly affected Al^{3+}, Ca^{2+} saturation, and SO_4^{2-}-S ($p < 0.05$). Coefficient of Variation ranged from 2.5% to 27.0%.

In the absence of liming, gypsum rates influenced exchangeable Al^{3+}, Ca^{2+}, Mg^{2+}, K^+, and SO_4^{2-}-S contents, leading to changes in base saturation, Ca^{2+} saturation, and Mg^{2+} saturation. Such findings may be attributed to the high solubility of gypsum (0.241 g 100 mL^{-1} water at 20 °C), which, when added to the soil surface, provides calcium and sulfur (VITTI, 2012; VITTI et al., 2015).

Although the soil initially exhibited high SO_4^{2-}-S availability (3.1–6.0 mg dm^{-3}), as indicated by the soil test value interpretation class (PAULETTI; MOTTA, 2017), the exchangeable Ca^{2+} content was low (0.5–1.0 $cmol_c$ dm^{-3}). Thus, gypsum rates, which varied greatly (0–4308 kg ha^{-1}), afforded significant differences in Ca^{2+} availability and, consequently, base saturation and Ca^{2+} saturation.

Gypsum application induced alterations in Mg^{2+}, K^+, and SO_4^{2-}-S levels in the soil, creating neutral ionic pairs ($MgSO_4$ and K_2SO_4) that easily leached to deeper layers, potentially reducing the availability of Mg and K to crops over time (CREMON et al., 2009; RAIJ, 2008; ZAMBROSI et al., 2007; ZANDONÁ et al., 2015). This leaching could lead to deficiencies in these essential nutrients, hampering root access.

The joint use of lime and gypsum effectively neutralized soil acidity by eliminating phytotoxic Al^{3+} and increasing pH H_2O. Lime's hydrolysis generated OH^- ions, rendering H^+ and Al^{3+} non-toxic to plants (BAMBOLIM et al., 2015; SANTOS et al., 2016). Liming also bolstered Ca^{2+} and Mg^{2+} availability in solution, crucial for soybean growth (RODRIGUES et al., 2017). Gypsum potentially contributed to reducing Al^{3+} up to 20 cm depth, enhancing Ca^{2+} and SO_4^{2-}-S in subsurface layers, diminishing Al^{3+} activity (ALCARDE; RODELLA, 2003). This interaction increased the saturation of base cations while reducing phytotoxic Al^{3+} (COSTA et al., 2015; ZAMBROSI et al., 2007).

Analyzing the interaction effects of liming and gypsum rates (Table 6), the combined use neutralized Al^{3+} entirely, not observed in treatments with gypsum alone. Gypsum with lime also heightened Ca^{2+} saturation but elevated Mg^{2+} saturation regardless of gypsum rate. Higher SO_4^{2-}-S levels occurred without lime at rates of 321 kg ha^{-1} and above.

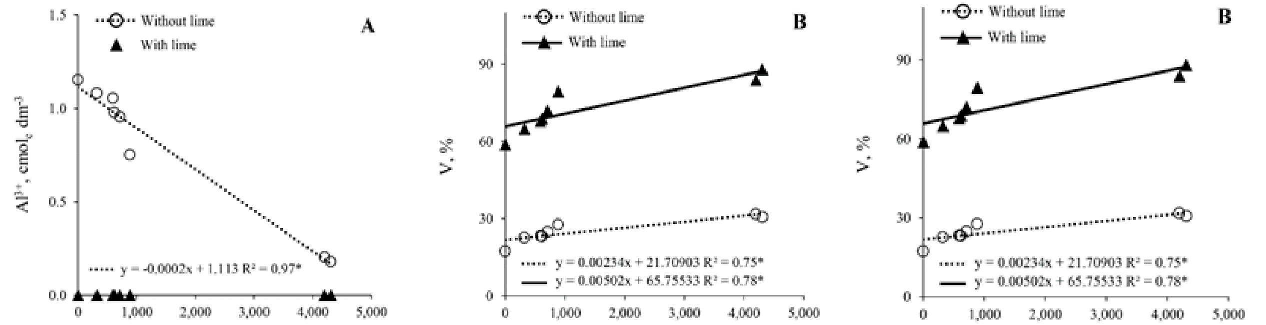
Table 6 – Interaction effects of Gypsum rate × Lime application on Al^{3+}, Ca^{2+} saturation, Mg^{2+} saturation, and SO_4^{2-}-S in a typical dystrophic Red-Yellow Latosol under soybean in Umuarama, Paraná, Brazil, 2017/2018

Lime Application	Gypsum rate (kg ha^{-1})*							
	0	321	592	619	710	887	4198	4308
	Al^{3+} ($cmol_c$ dm^{-3})							
Unlimed	1.15 a	1.08 a	1.05 a	0.98 a	0.96 a	0.75 a	0.20 a	0.18 a
Limed	0.00 b	0.00 b	0.00 b	0.00 b	0.00 b	0.00 b	0.00 b	0.00 b
	Ca^{2+} saturation (%)							
Unlimed	24.2 b	27.5 b	27.5 b	31.0 b	38.1 b	45.9 b	72.1 b	76.5 a
Limed	57.3 a	58.1 a	61.3 a	61.3 a	68.0 a	69.6 a	78.9 a	79.9 a
	Mg^{2+} saturation (%)							
Unlimed	13.6 b	13.5 b	14.6 b	14.0 b	11.6 b	13.3 b	10.1 b	9.0 b
Limed	33.9 a	31.0 a	30.0 a	27.6 a	24.2 a	24.0 a	18.3 a	17.6 a
	SO_4^{2-}-S (mg dm^{-3})							
Unlimed	4.2 a	6.0 a	6.7 a	8.1 a	9.3 a	10.0 a	11.3 a	12.3 a
Limed	4.1 a	5.6 b	6.4 b	7.3 b	8.5 b	9.1 b	10.1 b	10.9 b

Means within rows followed by different letters are significantly different by t-test (LSD, $p < 0.05$). * Significant at $p < 0.05$ by the F-test.
Source: research data.

In the absence of lime, rates beyond 4 t ha^{-1} gypsum reduced Al^{3+} (Figure 3A) by converting it to less harmful forms (ZAMBROSI et al., 2008). Lime combined with gypsum resulted in complete neutralization of exchangeable aluminum, forming harmless aluminum hydroxide ($Al(OH)_3$), as reported by Souza et al. (1995), Rheinheimer et al. (2000), and Meert et al. (2016).

Figure 3 – (A) Al^{3+} content, (B) base saturation, and (C) pH H_2O of a typical dystrophic Red-Yellow Latosol under soybean treated with different gypsum rates combined or not with lime. Umuarama, Paraná, Brazil, 2017/2018



Source: research data.

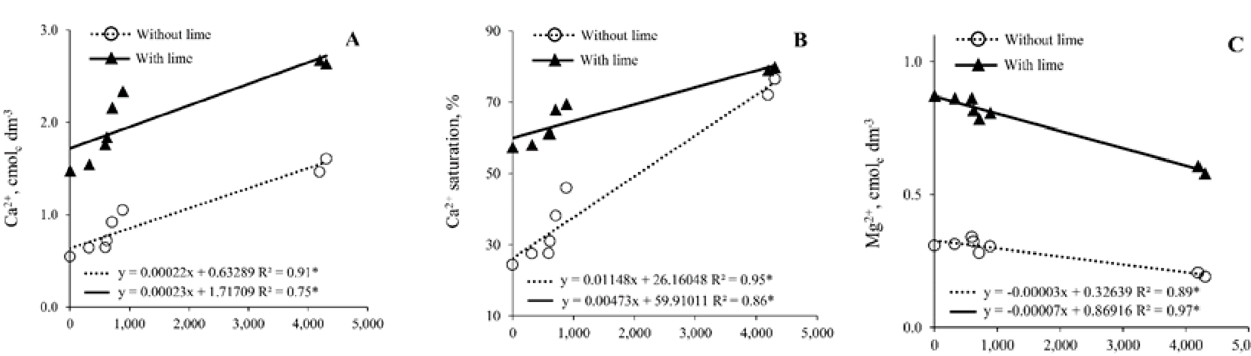
Base saturation increased linearly with gypsum dose, regardless of liming (Figure 3B); nevertheless, base saturation values were higher in limed treatments. These effects may be explained by the increase in calcium and magnesium contents from liming, which, in turn, increases their contribution to CEC (pH 7.0). In treatments without gypsum application, liming increased base saturation to the recommended value for soybean, namely 60% (PAULETTI; MOTTA, 2017). In treatments combining gypsum and lime, base saturation was higher than the recommended value.

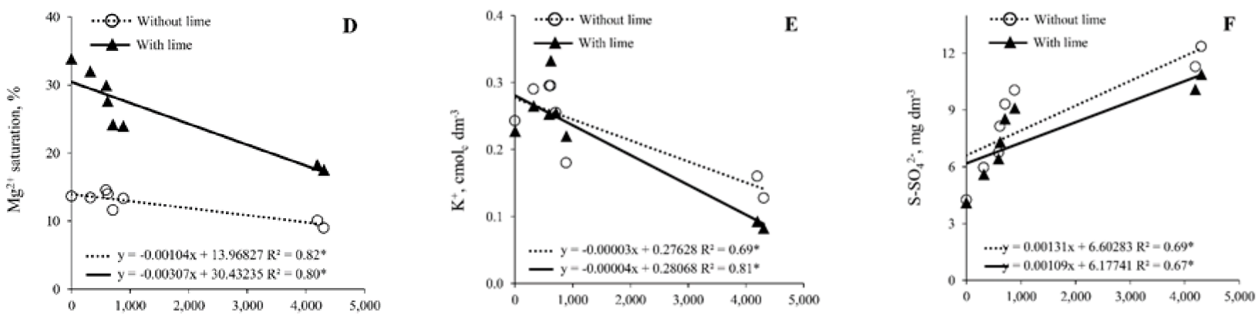
In the absence of liming, base saturation increased linearly with gypsum rate, albeit in an inefficient way. Such a behavior is probably due to lower calcium retention up to 20 cm depth, given that gypsum promotes the leaching of calcium to deeper soil layers, resulting in a less prominent increase in base saturation compared with liming. Furthermore, lime provides magnesium, which also contributes to the base saturation of soil. A similar result was reported by Costa et al. (2015), who found that base saturation increased with gypsum application in the absence of lime because of an increase in exchangeable calcium.

pH H_2O increased with liming but was not influenced by gypsum rate (Figure 3C). The initial soil pH H_2O (4.63) was very low (PAULETTI; MOTTA, 2017). Liming increased pH values to above 5.5. Under these pH conditions, exchangeable aluminum (Al^{3+}) becomes unavailable and the availability of essential nutrients increases (PROCHNOW; CANTARELLA, 2015).

The application of gypsum significantly influenced soil nutrient dynamics. Calcium (Ca^{2+}) content showed a linear increase with rising gypsum rates (Figure 4A), accentuated by combined gypsum and lime application, aligning with previous studies (BOSSOLANI, 2018; SORATTO et al., 2010). Liming particularly improved Ca^{2+} availability, in line with prior research (CAIRES et al., 2004, 2011; SORATTO; CRUSCIOL, 2008). Without lime, gypsum application beyond 4 t ha^{-1} resulted in intermediate $Ca2^{+}$ availability, contrasting with the high levels achieved (2.1–6.0 cmol$_c$ dm^{-3}) when combined with lime, underscoring the pivotal role of lime in augmenting soil exchangeable calcium.

Figure 4 – (A) Ca^{2+} content, (B) Ca^{2+} saturation, (C) Mg^{2+} content, (D) Mg^{2+} saturation, (E) K^{+} content, and (F) SO_4^{2-}-S content of a typical dystrophic Red-Yellow Latosol under soybean treated with different gypsum rates combined or not with lime. Umuarama, Paraná, Brazil, 2017/2018





Source: research data.

The impact of lime and gypsum on soil nutrient dynamics and their interplay significantly influences soil nutrient availability and saturation. Calcium (Ca^{2+}) saturation (Figure 4B) showed varying levels from under 50% at lower gypsum rates to over 70% at higher rates without lime. In conjunction with lime, levels exceeded 60% with gypsum rates surpassing 592 kg ha^{-1}, indicating lime's role in enhancing Ca^{2+} saturation more efficiently than gypsum alone. Higher Ca^{2+} saturation, classified as above 34%, correlates with increased soybean yields according to EMBRAPA (2008) and other studies (BORKERT et al., 2006; SFREDO et al., 2006), emphasizing its importance over Al^{3+} saturation (GUIMARÃES et al., 2015).

Exchangeable magnesium (Mg^{2+}) decreased linearly with increasing gypsum rates, particularly evident without lime, dropping to very low levels. Lime application, however, sustained intermediate Mg2+ availability despite the decrease at high gypsum doses (>4 t ha^{-1}). Mg^{2+} leaching in sandy soils, owing to their lower CEC, was notable (ZOCA; PENN, 2017). Mg^{2+} saturation rose with liming, yet higher gypsum rates reduced its saturation due to increased Ca^{2+} availability, leading to competition for soil adsorption sites between Ca^{2+} and Mg^{2+}.

Exchangeable potassium (K^+) increased across treatments due to fertilizer application during sowing but decreased linearly with rising gypsum rates, especially at higher rates (>4 t ha^{-1}), potentially due to increased Ca^{2+} availability. The absence of lime sustained higher K^+ availability at lower gypsum rates but led to intermediate availability at higher rates, indicating gypsum-induced K^+ leaching.

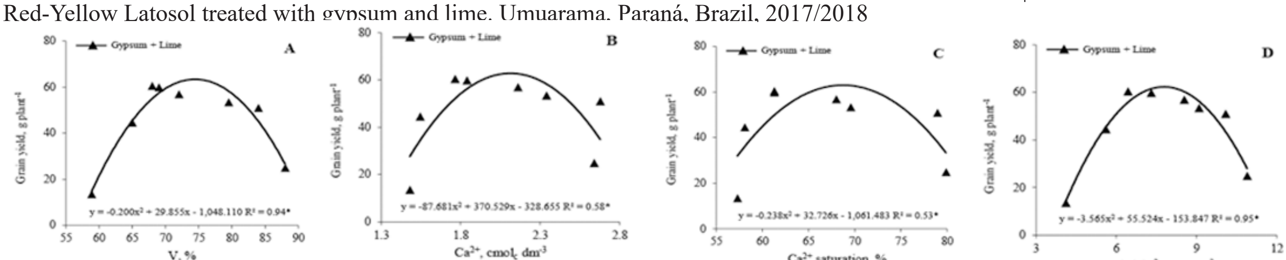
The complex relationship among gypsum, lime, and soil nutrients highlights the pivotal role of liming in enhancing soil calcium and magnesium while modulating potassium levels, thus affecting soil nutrient availability and saturation. In a clayey Latosol, K+ complexation by inorganic anions favored adsorption, reducing leaching, while in the sandy Latosol examined, lower organic matter resulted in increased leaching potential. SO_4^{2-}-S content consistently rose with gypsum rates, reaching very high levels (>6.0 mg dm^{-3}) at rates ≥592 kg ha^{-1}, irrespective of liming, aligning with previous findings (SCHMIDT et al., 2016; SORATTO; CRUSCIOL, 2008).

3.3Acidity indices for gypsum application

The integration of lime with agricultural gypsum significantly boosted soybean yield by enhancing Ca^{2+} and SO_4^{2-}-S availability. Gypsum, due to its high solubility, penetrates deep soil layers, necessitating lime to address nutrient deficiencies, especially Mg^{2+}, and to rectify pH imbalances inherent in sandy soils. pH regulation significantly influences soybean nutrient accessibility, particularly the neutralization of toxic Al^{3+} ions in the upper soil layer (0–10 cm), crucial for root development and overall productivity.

Soybean yield showed a quadratic increase concerning base saturation, exchangeable Ca^{2+}, Ca^{2+} saturation, and SO_4^{2-}-S (Figure 5). While gypsum application initially boosted yield (Figure 5A), doses surpassing 4 t ha^{-1} led to reduced yields, likely due to excess calcium and sulfur depleting soil nutrients (MAHAN, 2003). The saturation of ions intensified bond strengths between cations (Ca, K, Mg) and anions (SO_4^{2-}), fostering leaching of magnesium and potassium to deeper layers (CAIRES et al., 2003; RAIJ et al., 2008).

Figure 5 – Soybean yield as a function of (A) base saturation, (B) Ca^{2+}, (C) Ca^{2+} saturation, and (D) SO_4^{2-}-S in a typical dystrophic Red-Yellow Latosol treated with gypsum and lime, Umuarama, Paraná, Brazil, 2017/2018



Source: research data.

The relationship between soil amendments and soybean yield reveals critical insights into maximizing productivity. Regression analysis highlighted that peak soybean yield aligns with a 75% base saturation (Figure 5A), exceeding the recommended 60% level for soybean (PAULETTI; MOTTA, 2017; RAIJ et al., 1997). This suggests that gypsum, in tandem with lime, enriches base saturation by supplying exchangeable base cations like Ca^{2+}.

Soybean yield surged with increased exchangeable Ca^{2+} (Figure 5B), stimulating growth and productivity. However, excessive Ca^{2+} from high gypsum rates (>4 t ha^{-1}) decreased yields. The optimal yield correlated with 2 $cmol_c$ dm^{-3} Ca^{2+}, an intermediate range according to different soil classification systems (PAULETTI; MOTTA, 2017; CQFS-RS/SC, 2016), showcasing the substantial impact of increased Ca^{2+} content on soybean grain yield.

Ca^{2+} saturation played a pivotal role in soybean yield, showing an increase with rising gypsum rate (Figure 5C). However, excessively high gypsum rates reduced grain yield due to an excessive increase in Ca^{2+} saturation. The highest grain yield (63.49 g) aligned with a Ca^{2+} saturation of 69%.

SO_4^{2-}-S content influenced crop yield positively (Figure 5D). Yet, at high levels induced by excessive gypsum rates (>4 t ha^{-1}), soybean yield decreased due to nutrient solution imbalances (MAHAN, 2003). The optimal soybean yield was estimated at an SO_4^{2-}-S content of 7.8 mg dm^{-3}, lower than recommended levels for meeting soybean's nutritional requirements.

The combined use of gypsum and lime substantially impacted soil chemical attributes, promoting a 75% base saturation associated with increased production. The interaction between gypsum and lime enhanced Ca^{2+} content, altering Ca^{2+} and Al^{3+} saturation and ultimately leading to high soybean yield, aligning with previous observations by Raij (2008) and Vitti et al. (2015). This highlights the potential for optimizing soil amendments to maximize soybean productivity in sandy Latosols with the adjusted target values of soil parameters (Table 7).

Table 7 – Target values for determining gypsum rates based on chemical analysis of the 0–20 cm layer of a typical dystrophic Red-Yellow Latosol under soybean treated with different gypsum rates combined or not with lime. Umuarama, Paraná, Brazil, 2017/2018

Criteria	Measurement Unit	Target Value
Base saturation	%	75
Ca^{2+} content	$cmol_c$ dm^{-3}	2.1
Ca^{2+} saturation	%	69
SO_4^{2-}-S content	mg dm^{-3}	7.8

Source: research data.

The fact that maximum soybean yield was achieved under an SO_4^{2-}-S content lower than the recommended might be related to the level of extraction of this nutrient by plants and to the nutritional requirements of the crop (TIECHER et al., 2016). An increase in sulfur concentration in soil increases nutrient absorption by plants, which favors the production of essential amino acids and coenzymes, resulting in high yields (MARSCHNER, 2012).

The proposed criteria may serve as a basis for gypsum recommendations for sandy Latosols, as they indicate critical levels of important chemical attributes associated with soil fertility. Application of these criteria when combining gypsum and lime may lead to savings and increased soybean yield in sandy soils.

4 Conclusion

Liming combined with gypsum at the maximum technical efficiency rate of 2239 kg ha^{-1} increased the yield of soybean grown in a sandy Latosol. Liming was efficient in increasing plant height, stem diameter, dry matter accumulation, pod number, grain number, and soybean yield. Base saturation, exchangeable Ca^{2+}, Ca^{2+} saturation, and SO_4^{2-}-S content can be used as gypsum application indices for sandy Latosols.

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