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Soil chemical modifications after cauliflower cultivation in response to gypsum and potassium applications

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ABSTRACT

Gypsum supplies Ca and Mg and reduces Al saturation in deep soil layers. After gypsum application, a K source must be applied to minimize soil cation displacement. Cauliflower's economic importance, its high S and K absorption, and lack of knowledge about its nutritional management drove the objective of studying the effects of gypsum and K_2O on soil attributes and cauliflower yield. A 5×5 factorial scheme of gypsum (0, 500, 1,000, 2,000, 4,000 kg/ha) and K_2O (0, 100, 180, 240, 360 kg/ha as KCl) doses was implemented with 3 replications, and two soil layers assessed. Gypsum increased Ca and S in 0-0.2 and 0.2-0.4 m soil layers. Cu, Fe, Mn, and Zn were not affected by the gypsum or K_2O. Soil B in 0-0.2 m layer decreased with gypsum. Increasing K_2O doses raised K and decreased Mg/K in 0-0.2 and 0.2-0.4 m layers. In 0.2-0.4 m layer, Al and potential acidity also increased by K_2O. Cauliflower productivity was not affected by gypsum, reaching 15.93 t/ha when 360 kg/ha of K_2O was applied. K_2O requires careful management to avoid increasing potential acidity and reducing Mg/K. Gypsum and K_2O optimize crop nutritional management to improve cauliflower productivity and soil quality.

Keywords: *Brassica oleracea* var. *botrytis*, agricultural amendments, calcium sulfate, K_2O, soil fertility.

RESUMO

Modificações químicas do solo após o cultivo de couve-flor em resposta à aplicação de gesso e potássio

O gesso fornece Ca e Mg e reduz a saturação de Al em camadas profundas do solo. Após a aplicação de gesso, é necessário aplicar uma fonte de K para minimizar o deslocamento de cátions no solo. A importância econômica da couve-flor, sua alta absorção de S e K, e a falta de conhecimento sobre seu manejo nutricional motivaram o objetivo de estudar os efeitos do gesso e do K_2O sobre os atributos do solo e a produtividade da couve-flor. Um esquema fatorial 5×5 foi implementado, com doses de gesso (0, 500, 1.000, 2.000, 4.000 kg/ha) e de K_2O (0, 100, 180, 240, 360 kg/ha como KCl), em 3 repetições, avaliando-se duas camadas do solo. O gesso aumentou os teores de Ca e S nas camadas de 0-0,2 m e 0,2-0,4 m. Cu, Fe, Mn e Zn não foram afetados pelo gesso ou pelo K_2O. O B do solo na camada de 0-0,2 m diminuiu com o gesso. Doses crescentes de K_2O aumentaram o teor de K e reduziram a relação Mg/K nas camadas de 0-0,2 m e 0,2-0,4 m. Na camada de 0,2-0,4 m, o Al e a acidez potencial também aumentaram com o K_2O. A produtividade da couve-flor não foi afetada pelo gesso, atingindo 15,93 t/ha quando 360 kg/ha de K_2O foram aplicados. O K_2O requer manejo cuidadoso para evitar o aumento da acidez potencial e a redução da relação Mg/K. O gesso e o K_2O otimizam o manejo nutricional da cultura para melhorar a produtividade da couve-flor e a qualidade do solo.

Palavras-chave: *Brassica oleracea* var. *botrytis*, corretivos agrícolas, sulfato de cálcio, K_2O, fertilidade do solo.

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Soil acidity is a limiting factor in crop production, especially in the tropics, because it limits the nutrient supply to plants and presents toxic contents of aluminum (Al^{3+}) (Agegnehu *et al*., 2021; Getaneh & Kidanemariam 2021). Limestone (lime) reduces the concentration of H^+ ions in soil solution, increases plant-available nutrients, and supplies calcium (Ca^{2+}) and magnesium (Mg^{2+}) (Ameyu 2019; Mohammed *et al*., 2021). However, lime is of low solubility, and its effects are mainly concentrated in the topsoil layer. Gypsum is applied to deliver nutrients in deeper soil layers (Caires & Guimarães, 2016; Tiecher *et al*., 2018; Besen *et al*., 2021).

Gypsum is a by-product of the acidulation of phosphate rock (apatite) with sulfuric acid (H_2SO_4) during the production of phosphoric acid (H_3PO_4). The average gypsum composition includes 17% sulfur (S), 31% calcium oxide (CaO), 0.2%

fluorine (F), and 0.7% phosphorus pentoxide (P_2O_5). The Ca^{2+} present in gypsum can displace Al^{3+}, potassium (K^+), and Mg^{2+} cations, which can further react with sulfate anions (SO_4^{2-}), creating a less toxic form of aluminum ($AlSO_4^+$) and neutral ion pairs (K_2SO_4, $MgSO_4$, $CaSO_4$), which are highly mobile in the soil profile (Tiecher *et al*., 2018).

Gypsum is more soluble than lime, and researchers point out that farmers should be careful using this amendment in sandy soils with low cation exchange capacity (CEC). Such soils are characterized by higher mobility of bases than clayey soils, which can consequently cause nutrient depletion, especially K^+, which is poorly adsorbed by soil colloids (Mantovani *et al*., 2017; Rashmi *et al*., 2018). Thus, potassic fertilizers must be carefully managed to avoid cation displacement from the topsoil after gypsum application and plant deficiencies.

Due to (i) the cauliflower (*Brassica oleracea* var. *botrytis* L.) food importance worldwide, (ii) its high economic value, (iii) its high sulphur and potassium absorption (Takeishi *et al*., 2009; Alvez *et al*., 2011), and (iv) the lack of scientific knowledge about crop nutritional management on cauliflower production that the study of gypsum and potassic fertilizers on soil cations must be implemented to this crop. Thus, this study aimed to evaluate cauliflower head production and soil chemical attributes managing gypsum and potassic fertilizers.

MATERIAL AND METHODS

The experiment was conducted from October 2nd, 2014 to January 10th, 2015. The experimental site (19º39'19"S; 47º57'27"W; 800 m altitude) is located on a medium-textured (21% clay) dystrophic Red Latosol (Oxisol) in the municipality of Uberaba-MG, Brazil. The local climate is Aw: tropical, hot, and humid, with a cold and dry winter. Mean precipitation and temperature during the experiment were 672.68 mm and 23.82ºC, respectively.

The chemical characteristics of the 0-0.2 and 0.2-0.4 m soil layers of the experimental area are presented in Table 1.

Table 1. Soil chemical characterization of the area before cauliflower planting at 0-0.2 and 0.2-0.4 m soil depth. Uberaba, IFTM, 2014.

pH	Ca	Mg	Al	H + Al	CEC	V	P	K	SB	S	SOM
$CaCl_2$	----------$mmol_c/dm^3$----------					%	----------mg/dm^3----------				g/dm^3
---------- **0-0.2 m** ----------											
4.66	9.00	2.20	3.90	33.70	48.40	31	47.67	138	15	10.09	36.33
---------- **0.2-0.4 m** ----------											
4.86	8.90	2.70	2.60	26.70	45.30	41	32.33	83	19	18.53	19.33

B	Cu	Fe	Mn	Zn	Ca/Mg	Ca/K	Mg/K
----------mg/dm^3----------							
---------- **0-0.2 m** ----------							
0.18	4.55	26	28	3.29	4.22	2.57	0.62
---------- **0.2-0.4 m** ----------							
0.18	3.61	25	18	1.89	1.52	4.25	3.48

Ca, Mg, Al = KCl solution (1 mol/L); H+Al = SMP buffer solution (pH 7.5); CEC = cation exchange capacity at pH 7; V = saturation of bases; P = resin; K = 0.05 mol/L HCl + H_2SO_4 0.0125 mol/L; SB = sum of bases; S = sulfate-phosphate/calcium; SOM. = soil organic matter (colorimetric method); B, Cu, Fe, Mn, Zn = DTPA (diethylene triamine penta acetic acid). Methodologies source: Raij *et al*. (2001).

Overall, liming was carried out in the experimental area to raise base saturation to 70%, as recommended by the Minas Gerais State Soil Fertility Commission (Fontes, 1999) for the cauliflower crop. A dose of 1,600 kg/ha of calcined limestone (Relative Power of Total Neutralization – RPTN = 120) was surface-applied by broadcasting and subsequently incorporated into the 0-0.2 m soil layer 40 days before seedling transplanting. During this period (40 days), the area was irrigated to improve the lime-soil reaction. After 35 days of lime application, the cropping area was prepared with a disk harrow followed by a light levelling harrow before planting bed preparation (0.2 m high).

The experimental design was randomized complete blocks with three replications in a 5x5 factorial scheme: five K_2O doses of 0,100, 180, 240, and 360 kg/ha applied as KCl, and five gypsum doses of 0, 500, 1,000, 2,000, and 4,000 kg/ha. The gypsum ($CaSO_4$) applied in this experiment presented 18% of Ca and 15% of S.

Each experimental unit was separated by 0.8 m, 1.1 m wide, and consisted of 12 plants with 0.8 m spacing between planting rows and 0.50 m between plants (experimental unit area: 10.56 m^2). The plant population was 25.000 cauliflowers

per hectare. Gypsum doses were spread over each parcel and mechanically incorporated (bedding rotary hoe) into the 0-0.2 m soil depth. The K_2O doses were manually applied in two planting furrows according to each treatment.

According to soil analysis (Table 1) and the cauliflower fertilizer recommendations (Fontes, 1999), 50 kg/ha of P_2O_5 (simple superphosphate), 20% of each K_2O dose (potassium chloride), and 20% of the recommended (150 kg/ha) N dose (urea) were applied at planting. Topdressing fertilization was done by applying N and K fertilizers as follows: 20% of the dose 15 days after planting (DAP), 30% of the dose 30 DAP, and 30% of the dose 45 DAP. Boron and molybdenum fertilization was also carried out via foliar during the cultivation of the seedlings (20 days after sown) and 15 and 30 days after transplanting the seedlings to the experimental site. Boron and molybdenum were supplied as boric acid and ammonium molybdate, respectively; doses were 1 g/L and 0.5 g/L (Raij *et al*., 1997), respectively, and were applied at a volume of 300 L/ha.

Cauliflower cultivar Sharon was used, which is resistant to black rot and has medium-sized and white-colored inflorescence with a mean weight from 0.9 to 1.2 kg. Its production cycle is 90-100 days, cultivated at the end of spring and summer. Cauliflower head productivity was assessed (t/ha) 66 days after seedling transplant to the field when the inflorescences were fully developed, with compact and firm heads. The evaluations were carried out considering eight central plants on each parcel.

Soil samples for chemical evaluations were collected after the cauliflower harvest; randomly, fifteen points were sampled at 0-0.2 and 0.2-0.4 m soil depth on each parcel, placed in plastic bags and dried at room temperature. The soil organic matter, P, K, Ca, Mg, Al, S, B, Cu, Fe, Mn, Zn, sum of bases (SB), cation exchange capacity (CEC), potential acidity (H^++Al^{3+}) were determined, and the ratios Mg/K, Ca/Mg, and Ca/K were calculated (Raij *et al*., 2001).

The data were submitted to analyses of variance (ANOVA) by the Ftest ($p \leq 0.05$). If significant differences among the groups were found, the backward stepwise selection was conducted to choose the best model (James *et al*., 2014). The response variables were each of the evaluated variables, and the explanatory variables or predictors were the effects linear, quadratic effects and the effects of the interaction (G, K, G^2, K^2, GK) of the gypsum (G) and potassium (K) doses. The Bayesian information criterion (BIC) was used to measure the quality of model adjustment for each response variable.

The model selection was based on low BIC values. The best model considered the parsimony, i.e., explanatory models were chosen with reasonable quality adjustment and the simplest possible. In addition, the t-test was used for the coefficients of the adjusted model to verify if they were significant ($p \leq 0.05$). A principal component analysis (multivariate statistical technique) of the evaluated variables was also performed. The analyses used software R (RStudio®) with MASS, LEAPS, EXPDES packages.

RESULTS AND DISCUSSION

The cauliflower head productivity (t/ha) presented no interaction ($p > 0.05$) between de gypsum and potassium fertilization, nor effects of the factor gypsum fertilization ($p > 0.05$); however, this plant variable was affected ($p \leq 0.05$) by the K_2O fertilization (Figure 1). The significant linear regression indicated that for each 1 kg/ha of K_2O fertilizer, an increase in 0.006962 t/ha of cauliflower head productivity is expected.

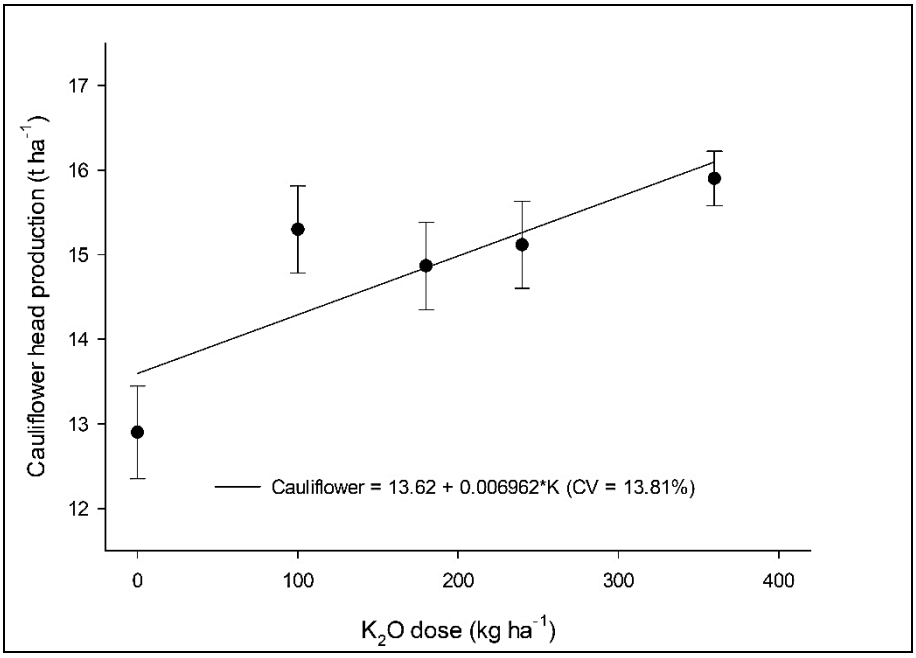

Figure 1. Cauliflower head production (t/ha) as a function of the K_2O doses (0, 100, 180, 240, 360 kg/ha) 66 days after seedling transplant to the crop field. Vertical bars = standard error of the mean (n = 3); CV (%) = coefficient of variation. Uberaba, IFTM, 2014.

The results of the soil variables are presented by soil layer and discussed together when the variable differs among treatments in both soil layers. No significant ($p>0.05$) interaction between the factors (gypsum and K_2O doses) was detected for the evaluated soil variables in both soil layers (0-0.2 and 0.2-0.4 m) (Tables 2 and 3). Only isolated factors (gypsum and K_2O doses) affected some soil variables; moreover, not all significant results were affected in both evaluated soil layers.

Table 2. Summary of analysis of variance (F test statistics) and averages of soil chemical attributes in the 0-0.2 m soil layer after cauliflower cultivation as a function of gypsum and potassium doses. Uberaba, IFTM, 2014.

G	SOM	pH	P_r	K	Ca	Mg	Al	H+Al	SB	CEC	S	B	Cu	Fe	Mn	Zn	Ca/Mg	Ca/K	Mg/K
Kg/ha	g/dm³	$CaCl_2$	Mg/dm³	---------- $mmol_c/dm^3$ ----------							---------- mg/dm^3 ----------								
0	21.93	4.67	40.53	2.38	13.63	2.79	3.50	34.40	18.80	53.20	35.40	0.25	2.42	29.18	32.44	2.55	5.31	6.29	1.32
500	21.33	4.71	41.93	2.15	14.66	2.46	3.40	34.12	19.30	53.12	47.47	0.23	2.28	29.55	32.26	2.49	7.33	7.53	1.18
1,000	22.07	4.73	42.27	2.33	17.07	2.63	3.24	34.50	20.76	56.51	51.92	0.26	2.52	29.49	34.77	2.75	8.34	8.29	1.14
2,000	20.67	4.84	43.60	2.19	15.13	2.51	2.90	33.60	20.22	53.36	61.12	0.21	2.64	30.16	34.00	2.79	6.74	7.94	1.41
4,000	20.93	4.73	37.67	2.04	18.29	2.45	2.90	33.87	22.04	56.88	56.00	0.24	2.52	29.28	31.88	2.35	7.30	10.80	1.62
K_2O Kg/ha																			
0	21.33	4.66	40.07	1.28	14.68	2.59	3.88	33.53	18.52	52.05	51.18	0.25	2.42	28.25	32.33	2.33	6.45	11.90	2.07
100	20.81	4.78	38.47	2.20	15.16	2.41	3.13	31.60	19.77	51.37	47.70	0.23	2.40	29.67	32.43	2.63	6.88	8.06	1.37
180	22.00	4.66	43.60	2.13	15.44	2.51	3.27	39.66	20.92	60.58	48.00	0.25	2.64	31.13	34.22	3.00	7.29	8.21	1.23
240	21.93	4.78	41.47	2.36	15.34	2.79	3.21	34.09	21.04	55.70	51.64	0.23	2.49	29.75	33.95	2.40	6.84	7.21	1.24
360	21.07	4.74	42.40	3.11	15.04	2.22	3.24	31.60	20.83	53.35	53.39	0.24	2.45	28.85	32.43	2.58	7.54	5.46	0.76
Mean	21.33	4.74	41.20	2.22	15.13	2.51	3.24	34.10	20.22	54.61	50.38	0.24	2.48	29.53	33.07	2.59	7.00	8.17	1.33
F_G	0.60^{ns}	1.24^{ns}	0.78^{ns}	0.84^{ns}	4.65^{*}	1.10^{ns}	1.05^{ns}	0.04^{ns}	3.67^{*}	0.72^{ns}	7.68^{*}	5.94^{*}	0.83^{ns}	0.22^{ns}	1.08^{ns}	0.77^{ns}	3.26^{ns}	4.81^{ns}	1.25^{ns}
F_K	0.46^{ns}	1.89^{ns}	0.62^{ns}	18.49^{*}	0.81^{ns}	0.82^{ns}	1.53^{ns}	3.32^{*}	1.81^{ns}	2.78^{ns}	0.46^{ns}	1.35^{ns}	0.35^{ns}	1.77^{ns}	0.74^{ns}	1.30^{ns}	0.44^{ns}	10.05^{ns}	7.39^{*}
F_{GxK}	1.10^{ns}	0.66^{ns}	1.00^{ns}	0.65^{ns}	0.74^{ns}	0.57^{ns}	0.60^{ns}	0.58^{ns}	0.56^{ns}	0.47^{ns}	1.81^{ns}	0.33^{ns}	1.61^{ns}	1.10^{ns}	1.76^{ns}	1.45^{ns}	0.92^{ns}	1.30^{ns}	0.78^{ns}
CV (%)	14.26	3.65	23.91	26.52	21.51	36.39	28.30	20.61	18.49	15.80	27.18	12.99	15.08	10.73	13.54	34.26	33.20	35.66	50.29

G = gypsum doses; K_2O = K_2O doses; SOM = soil organic matter (colorimetric method); Pr = anion-exchange resin method of P extraction; SB = sum of bases; CEC = cation exchange capacity; ns = not significant; *significant at $p\leq0.05$ by the F-test; CV (%) = coefficient of variation.

Table 3. Summary of analysis of variance (F test statistics) and averages of soil chemical attributes in the 0.2-0.4 m soil layer after cauliflower cultivation as a function of gypsum and potassium doses. Uberaba, IFTM, 2014.

G	OM	pH	P_r	K	Ca	Mg	Al	H+Al	SB	CEC	S	B	Cu	Fe	Mn	Zn	Ca/Mg	Ca/K	Mg/K
Kg/ha	g/dm³	$CaCl_2$	Mg/dm³	---------- $mmol_c/dm^3$ ----------							---------- mg/dm^3 ----------								
0	18.67	4.98	27.33	2.36	9.50	2.58	2.38	29.73	14.47	44.09	42.02	0.23	5.21	29.21	25.30	2.71	3.99	4.39	1.12
500	20.67	4.93	28.27	2.41	9.87	2.63	2.25	30.88	15.18	45.92	49.76	0.24	3.31	26.80	23.50	1.95	3.93	4.87	1.20
1,000	18.53	4.93	31.07	2.59	11.31	2.71	1.96	29.64	16.36	46.24	46.08	0.23	4.10	29.60	23.73	2.46	4.74	3.98	1.20
2,000	19.93	4.93	26.67	2.40	12.39	2.39	1.84	30.48	17.74	48.13	53.69	0.21	4.98	32.26	24.98	2.42	4.91	4.95	1.13
4,000	18.40	4.91	30.27	2.41	12.77	2.83	1.91	29.87	17.57	47.44	60.25	0.21	3.11	28.61	23.58	1.78	5.70	5.95	1.09
K_2O Kg/ha																			
0	18.64	4.98	26.87	1.82	10.80	2.68	1.47	27.46	15.30	42.76	51.20	0.22	4.49	29.53	24.09	2.21	4.19	6.37	1.58
100	18.84	4.95	28.00	2.43	10.37	2.70	1.81	27.00	15.51	42.51	48.23	0.23	4.75	29.05	23.86	2.46	4.10	4.51	1.19
180	19.67	4.89	28.64	2.31	11.23	2.59	2.33	29.20	16.12	45.32	52.20	0.22	5.06	29.27	24.70	2.64	4.70	4.91	1.14
240	19.93	4.94	32.33	2.68	12.62	2.96	1.94	28.80	18.30	46.98	49.75	0.22	3.13	30.66	24.32	2.08	5.01	4.76	1.09
360	19.13	4.79	27.80	3.06	10.82	2.21	2.79	38.13	16.10	54.23	50.41	0.23	3.25	27.97	24.12	1.89	5.24	3.59	0.74

Mean	19.24	4.94	28.72	2.43	11.17	2.63	2.07	30.12	16.26	46.36	50.36	0.22	4.14	29.30	24.22	2.26	4.65	4.83	1.15
F_G	1.72^{ns}	0.41^{ns}	0.60^{ns}	0.75^{ns}	5.24*	0.89^{ns}	0.64^{ns}	0.09^{ns}	5.03^{ns}	0.84^{ns}	3.96*	1.73^{ns}	1.46^{ns}	1.88^{ns}	0.37^{ns}	1.18^{ns}	4.52*	2.65^{ns}	0.23^{ns}
F_K	0.52^{ns}	3.08*	0.97^{ns}	12.73*	1.85^{ns}	2.46^{ns}	2.98*	8.57*	3.44^{ns}	7.93*	0.17^{ns}	0.24^{ns}	1.29^{ns}	0.30^{ns}	0.06^{ns}	0.67^{ns}	1.60^{ns}	6.57^{ns}	8.27*
F_{GxK}	1.49^{ns}	0.60^{ns}	1.02^{ns}	0.94^{ns}	1.31^{ns}	1.26^{ns}	0.92^{ns}	0.36^{ns}	1.37^{ns}	0.62^{ns}	0.58^{ns}	0.75^{ns}	0.41^{ns}	0.52	0.79^{ns}	0.64^{ns}	0.92^{ns}	0.49^{ns}	0.65^{ns}
CV (%)	15.46	3.45	32.93	20.36	22.13	25.77	54.99	20.11	15.28	14.16	26.79	18.04	74.30	19.30	21.21	62.66	36.77	31.99	35.14

G = gypsum doses; K_2O = K_2O doses; SOM = soil organic matter (colorimetric method); Pr = anion-exchange resin method of P extraction; SB = sum of bases; CEC = cation exchange capacity; ns = not significant; *significant at p≤0.05 by the F-test; CV (%) = coefficient of variation.

In the 0-0.2 m soil layer, Ca, S, and B contents and the sum of bases (SB) varied according to gypsum doses. The K_2O doses influenced the soil K content, the potential acidity (H+Al), and the Mg/K ratio (Table 2). In the 0.2-0.4 m soil layer, gypsum doses affected Ca and S contents and the Ca/Mg ratio. In this same layer, the K_2O doses altered the soil pH, potential acidity (H+Al), cation exchange capacity, Mg/K ratio, and K content in the soil (Table 3).

Soil variables with no significant differences among factor levels

Tables 2 and 3 indicated that the average soil organic matter (OM) content was 21.33 g/dm^3 in the 0-0.2 m layer and about 9% lower than the OM present in the 0.2-0.4 m layer (19.24 g dm^{-3}). The tables also show that soil P status was 41.20 and 28.72 mg/dm^3 in the 0-0.2 and 0.2-0.4 m soil layers, respectively, a difference of about 43% between soil layers. Similarly, the soil Mg content varied between soil layers but not among doses. The soil Mg content was 2.51 and 2.63 mmol$_c$/dm^3 in the 0-0.2 and 0.2-0.4 m soil layers, respectively. According to Alvarez *et al*. (1999), the soil OM, P, and K content were considered "low-median", "good to very good", and "very good" levels in the soil, respectively ("good" means a content higher than the critical level for plant normal development). For Raij *et al*. (1997), the P contents in the present study are within the median content range of 26-60 mg/dm^3.

Contents of Cu, Fe, Mn, and Zn in both soil layers were not significantly affected by the gypsum and K_2O factors (Tables 2 and 3). Mean contents of Cu, Fe, Mn, and Zn were respectively: 2.48, 29.53, 33.0, 2.59 mg/dm^3 in the 0-0.2 m soil layer, and 4.14, 29.30, 24.22, 2.26 mg/dm^3 in the 0.2-0.4 m layer. According to Alvarez *et al*. (1999), Cu. Fe, Mn, and Zn contents in this study are classified as high for Cu (>1.8 mg/dm^3), high for Mn (>12 mg/dm^3), and high for Zn (>2.2 mg/dm^3), and median for Fe (19-30 mg/dm^3).

Soil variables with significant differences among factor levels

The gypsum doses significantly influenced soil calcium contents in both evaluated soil layers (Tables 2 and 3). In the 0-0.2 m layer, the treatment with 4,000 kg gypsum/ha produced 18.15 mmol$_c$/dm^3 (Figure 2a), which, according to Alvarez *et al*. (1999), is considered a median content of soil Ca^{2+} for crops. In the same way, the soil Ca^{2+} content in the 0.2-0.4 m soil layer increased linearly with the application of gypsum, up to the maximum dose of 4,000 kg Ca/ha (Figure 2A). Every kg of gypsum added to the soil increased soil Ca content in the 0.2-0.4 m soil layer by 0.000838 mmol$_c$/dm^3. The maximum Ca^{2+} content in this soil layer was 13.27 mmol$_c$/dm^3 at 4,000 kg gypsum/ha, which is within the median average content: 12.1-24.0 mmol$_c$/dm^3, as pointed out by Alvarez *et al*. (1999).

The responses of the soil chemical attributes [soil Ca, S, B, and K content, sum of bases, potential acidity ($H^+ + Al^{3+}$), and Mg/K correlation] to the gypsum or K_2O doses in the 0-0.2 m soil layer are presented in Figure 2.

The responses of the soil chemical attributes [soil Ca, S, B, and K content, sum of bases, potential acidity ($H^+ + Al^{3+}$), and Mg/K correlation] to the gypsum or K_2O doses in the 0.2-0.4 m soil layer are presented in Figure 3.

Potassium content showed a linear increase in the 0-0.2 m soil layer (Figure 2C) in increments of 0.0045484 mmolc/dm^3 for each kg of K_2O applied (Figure 3B). The potassium content in this layer at the maximum K_2O dose (360 kg/ha) was 3.06 mmol$_c$/dm. Potassium content at the 0.2-0.4 m soil depth (Table 3) also increased linearly in response to applying K_2O (Figure 3B). It indicated that each kg of K_2O applied increased soil K content by 0.0032125 mmol$_c$/dm^3 in this layer, reaching the content of 3.05 mmol$_c$/dm^3 at 360 kg K_2O/ha. According to Alvarez *et al*. (1999), K contents in the present study are classified as "good" (between 1.8 and 3.10 mmol$_c$/dm^3).

In the 0.2-0.4 m soil layer, Al^{3+} increased linearly in response to potassium doses (Figure 3C); such an effect was not observed on the Al^{3+} content in the 0-0.2 m soil layer (Table 2). Increments of 0.003350 mmol$_c$/dm^3 in the 0.2-0.4 m layer (Figure 3C) were observed for every kg of K_2O/ha, reaching the maximum content of 2.68 mmol$_c$/dm^3 using 360 kg K_2O/ha. Soil potential acidity ($H^+ + Al^{3+}$) in both soil layers was significantly affected by the K_2O doses (Tables 2 and 3). A quadratic model was found for this soil variable in the 0-0.2 m layer as a function of potassium treatment (Figure 2D). The maximum potential acidity (31.59 mmol$_c$/dm^3) was calculated at 171.17 kg K_2O/ha; however, in the 0.2-0.4 m

soil layer, a linear increase in potential acidity was observed (Figure 3C). The Al^{3+} and potential acidity ($H^+ + Al^{3+}$) contents were classified as median levels, according to Alvarez *et al*. (1999).

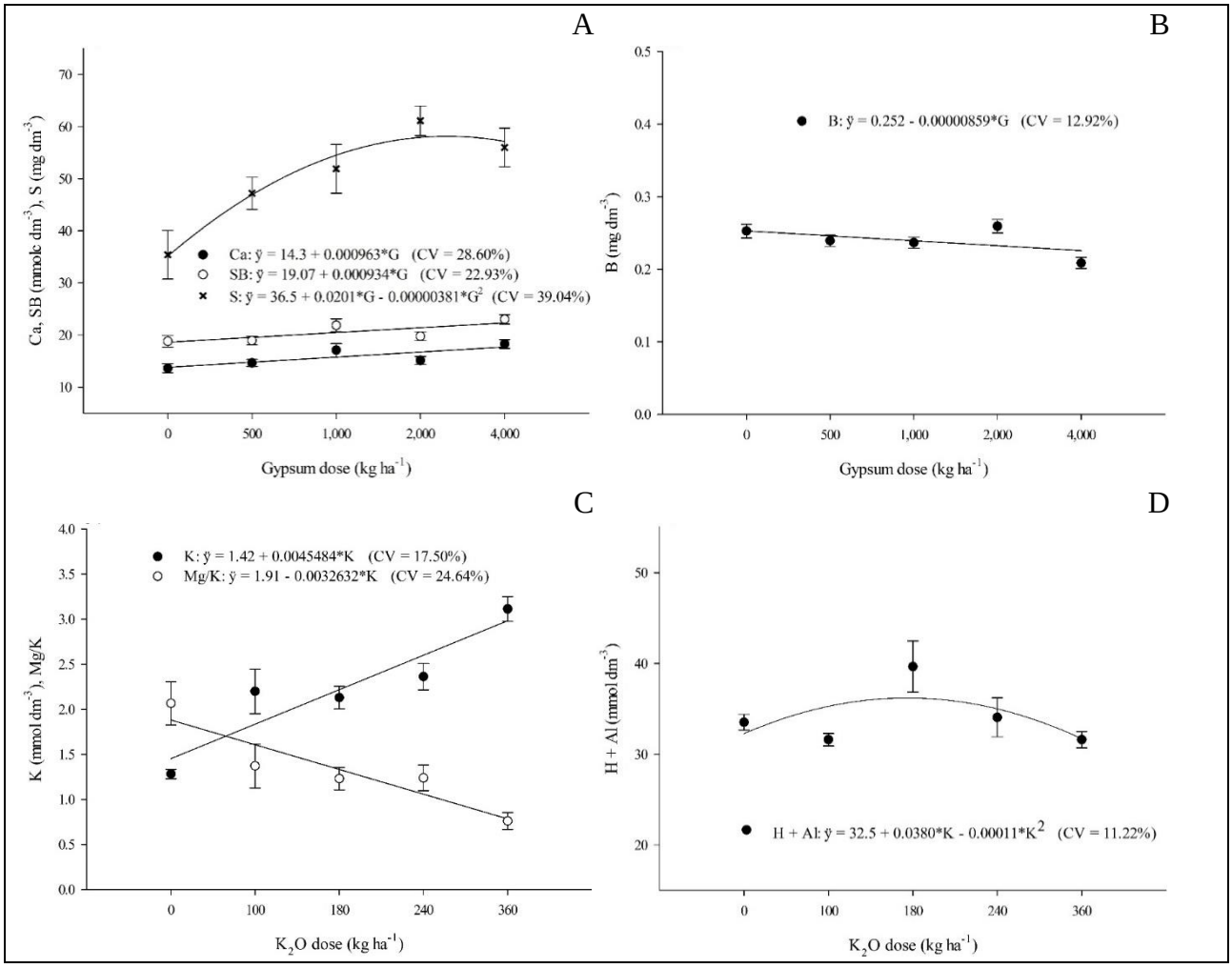

Figure 2. Soil calcium, base sum, sulfur (A), boron (B); potassium, magnesium/potassium relation (C), and soil potential acidity (D), as a function of gypsum and potassium doses at 0-0.2 m soil depth in the cauliflower production area. Ca = calcium; SB = sum of bases; B = boron; K = potassium; Mg/K = magnesium/potassium relation; $H^+ + Al^{3+}$ = potential acidity; K_2O = potassium; Vertical bars = standard error of the mean (n = 3); CV (%) = coefficient of variation. Uberaba, IFTM, 2015.

The sum of bases (SB) in the 0-0.2 m layer was significantly affected by the application of gypsum (Table 2); such an effect was not observed on the SB in the 0.2-0.4 m soil layer (Table 3). Figure 2A shows 0.000934 $mmol_c/dm^3$ increments of SB for every kg of gypsum applied per hectare. In the present study, SB content in the 0-0.2 m layer is classified as medium (18.1-36.0 $mmol_c/dm^3$), and in the 0.2-0.4 m layer, is classified as low (6.1-18.0 $mmol_c/dm^3$) (Alvarez *et al*., 1999). Increased SB contents in response to gypsum applications are likely due to higher Ca^{2+} contents in the 0-0.2 m layer (Figure 2A) after the gypsum solubilization.

Figure 3C (0.2-0.4 m soil layer) shows that a significant linear increase of CEC in response to K_2O doses was found (Table 3); such an effect was not observed on the CEC in the 0-0.2 m soil layer (Table 2). The 360 kg K_2O/ha treatment caused the highest CEC in the 0.2-0.4 m layer, 54.08 $mmol_c/dm^3$ (Figure 3D). CEC values observed in this study are within the 43.1-86.0 $mmol_c/dm^3$ range, classified as a median level (Alvarez *et al*., 1999).

In the 0-0.2 m layer (Table 2), a quadratic model was found for soil S content (Figure 2A), in which the highest content (55.94 mg/dm^3) was achieved when 2637.80 kg gypsum/ha was applied. In the 0.2-0.4 m layer (Table 3), gypsum doses performed a positive linear effect in soil S content (Figure 3A), with increments of 0.004075 mg/dm^3 for every kg of applied gypsum. According to Raij *et al*. (1997), S contents above 10 mg/dm^3, as observed in this study, are considered high.

A significant linear decrease in soil boron (B) content was observed with gypsum doses in the 0-0.2 m soil layer (Figure 2B). The soil B content in the topsoil layer diminished by 0.00000859 mg/dm^3 for every kg of gypsum added to the soil. Figure 2B shows that the maximum and minimum B contents in the 0-0.2 m layer at 0 and 4,000 kg gypsum/ha

were 0.25 and 0.22 mg/dm^3, respectively. The mean B content in the 0.2-0.4 m layer was 0.22 mg/dm^3 (Table 3), and no significant effect of applying gypsum or K_2O was observed. Boron content observed in the present experiment in both layers is considered low (0.16-0.35 mg/dm^3) by Alvarez *et al*. (1999) and median (0.21-0.60 mg/dm^3) by Raij *et al*. (1997). In cauliflower, boron deficiency symptoms are dark spots on the inflorescences and the cavity in the main stem. Such symptoms, however, were not observed in the present study.

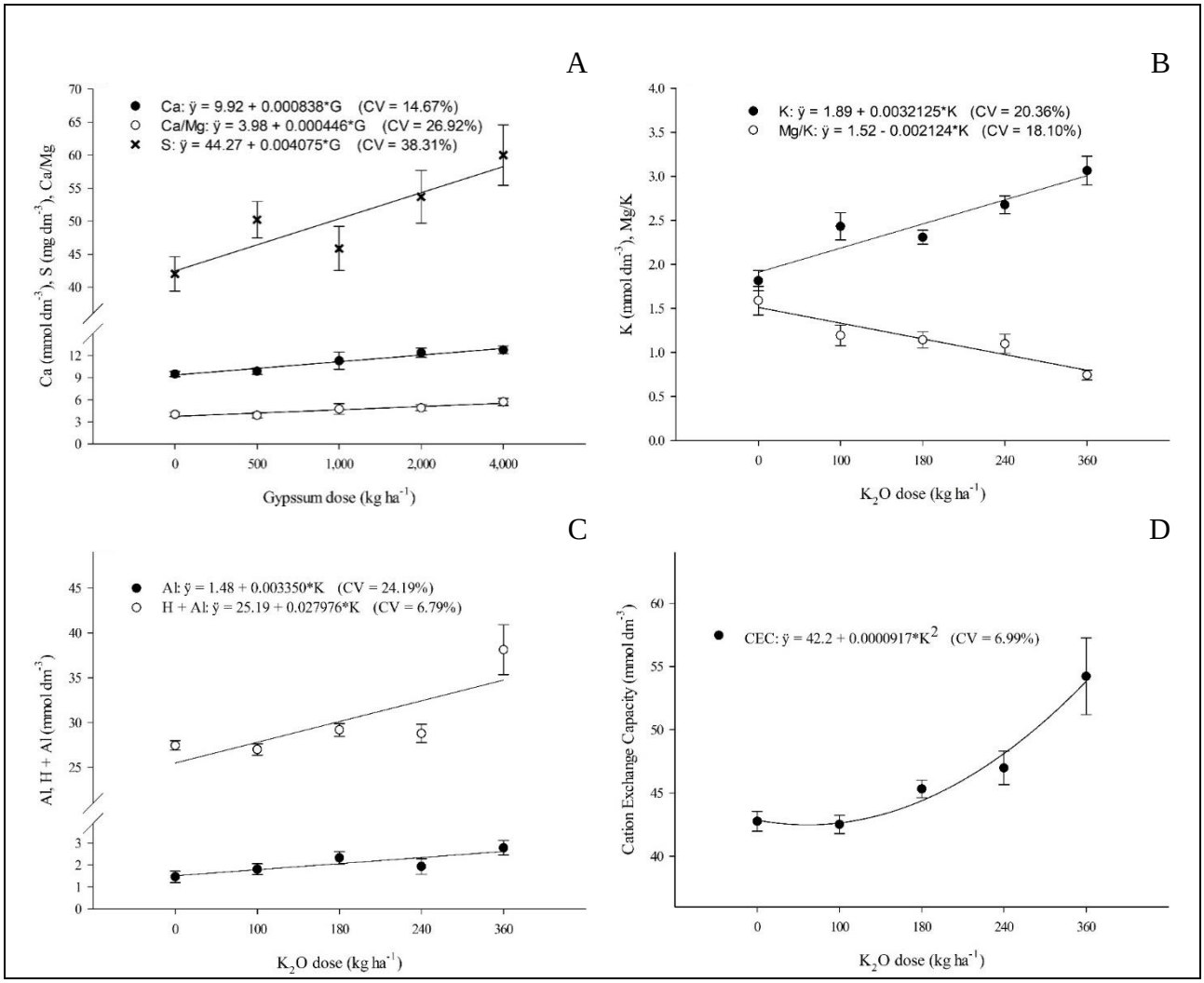

Figure 3. Soil calcium, sulfur, calcium/magnesium relation (A); soil potassium and magnesium/potassium relation (B); soil aluminum and potential acidity (C); cation exchange capacity (D), as a function of gypsum and potassium doses at 0.2-0.4 m soil depth in the cauliflower production area. Ca = calcium; S = sulfur; Ca/Mg = calcium/magnesium relation; K = potassium; Mg/K = magnesium/potassium relation; $H^+ + Al^{3+}$ = potential acidity; Vertical bars = standard error of the mean (n = 3); CV (%) = coefficient of variation. Uberaba, IFTM, 2015.

In the 0.2-0.4 m layer, the Ca/Mg ratio was significantly affected by gypsum doses (Table 3); such an effect was not observed on the Ca/Mg in the 0-0.2 m soil layer (Table 3). Figure 3A shows a linear relation of this ratio with gypsum doses, increasing 0.000446 in the Ca/Mg relation for each kg of gypsum added per hectare.

Regarding the Mg/K ratio, only K_2O doses demonstrated significant effects in both evaluated soil layers (Tables 2 and 3). A linear decrease with K_2O doses was observed in the 0-0.2 m layer (Figure 2C). The highest and lowest Mg/K ratios in this layer, 1.91 and 0.73, were found in treatments with 0 and 360 kg K_2O/ha, respectively (Figure 2C). Like the top layer, the Mg/K ratio decreased linearly with K_2O doses in the 0.2-0.4 m soil layer (Figure 3B). The 0 and 360 kg K_2O/ha in this soil layer presented an Mg/K ratio of 1.52 and 0.75, respectively (Figure 3B).

Despite the significant differences observed in the Ca/Mg and Mg/K ratios, no differences ($p>0.05$) were detected for the Ca/K ratio, presenting an average of 8.17 and 4.53 in the 0-0.2 and 0.2-0.4 m soil layers, respectively.

Principal component analysis (multivariate analysis)

The analysis of main components in the 0-0.2 m layer (Figure 4A), in general, indicated that gypsum doses equal to or greater than 1000 kg/ha, associated with the higher doses of K applied (e.g., 240 and 360 kg/ha) contributed the most to the soil Ca and K content. The rise in the Ca and K contents directly influences base saturation (V%), the sum of bases (SB), and Ca/Mg ratio. These rises can be observed in the upper right quadrant of Figure 4, emphasizing treatments T15, T19, T20, and T24, which present doses equal to or greater than 1000 and 240 kg/ha of gypsum and K_2O, respectively.

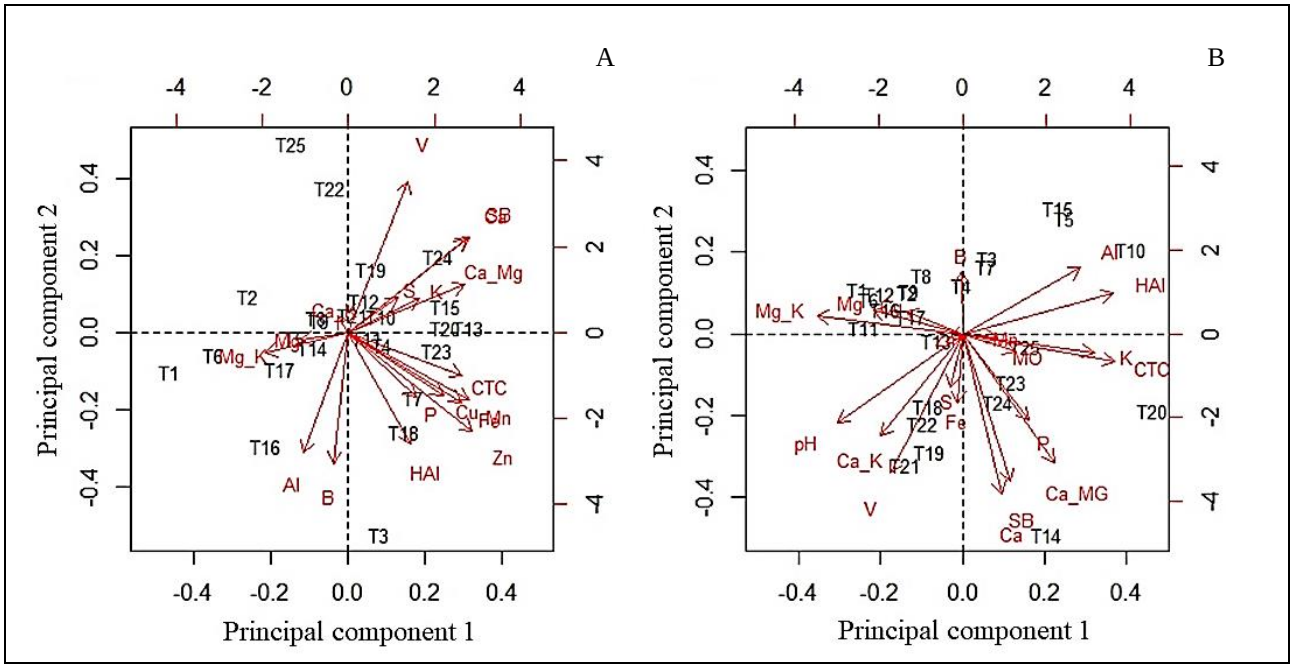

Figure 4. Analysis of main components in the 0-0.2 (A) and 0.2-0.4 m (B) soil layer as a function of gypsum and K2O doses after cauliflower crop. The treatments (T) are the gypsum (G, dose in kg/ha) and potassium (K, dose in kg/ha) combination, as follows: T1 = G0+K0; T2 = G0+K100; T3 = G0+K180; T4 = G0+K240; T5 = G0+K360; T6 = G500+K0; T7 = G500+K100; T8 = G500+K180; T9 = G500+K240; T10 = G500+K360; T11 = G1,000+K0; T12 = G1,000+K100; T13 = G1,000+K180; T14 = G1,000+K240; T15 = G1,000+K360; T16 = G2,000+K0; T17 = G2,000+K100; T18 = G2,000+K180; T19 = G2,000+K240; T20 = G2,000+K360; T21 = G4,000+K0; T22 = G4,000+K100; T23 = G4,000+K180; T24 = G4,000+K240; and, T25 = G4,000+K360. Uberaba, IFTM, 2015.

Conversely, the combinations of low gypsum doses (e.g., 0, 500, and 1,000 kg/ha) associated with the highest K_2O dose (360 kg/ha) were that most contributed to the highest contents of Al^{3+} and potential acidity ($H + Al^{3+}$) in the 0.2-0.4 m layer (Figure 4B). These contributions can be observed in the right upper quadrant of Figure 2 in treatments T5, T10, and T15.

The cauliflower head productivity was solely affected by the doses of potassic fertilization and presented no interference regarding the doses of gypsum because the soil sulfur content in both soil layers (0-0.2 and 0.2-0.4 m in Tables 2 and 3, respectively) was in the adequate general range of sulfur availability for plant development. Soil sulfur levels are considered sufficient for adequate plant development when superior to 10 mg/dm^3 (Vitti, 1989). However, the positive effect of potassium fertilization on cauliflower production was also observed by Charlo *et al*. (2021).

All the significant changes observed in the studied soil variables were indirectly and directly related to the elements added by gypsum (Ca and S) and K_2O (applied as KCl). Soil pH ($CaCl_2$), soil potential acidity ($H^+ + Al^{3+}$), Al^{3+}, and B content were secondarily affected by gypsum or K_2O fertilizations. The soil content of Ca, K, and S, the sum of soil bases, cation exchange capacity, and the ratios Ca/Mg and Mg/K in soil were expected to respond to the gypsum or K_2O fertilizations.

The soil pH reduction in the 0.2-0.4 m soil layer as a function of K_2O application can be attributed to the displacement of H^+ ions in the soil after binding K^+ to the negative soil loads, which created a higher content of free H^+ ions. Such variation in soil pH with potassium (KCl) application was also reported by Volf *et al*. (2018). Notably, the displacement intensity and movement of the H^+ cations in the soil depend on other variables, such as soil class and texture, organic matter content, temperature, nutrients available, and soil-crop management (Van Breemen *et al*., 1983).

In the same soil layer (0.2-0.4 m), the K_2O doses affected Al^{3+} contents and the potential acidity ($H^+ + Al^{3+}$). This effect can be related to the addition of cations such as K^+, which binds to negative charges in the soil, displacing Al^{3+} to the soil solution, which in turn contributes to soil acidity (Han *et al*., 2021; Souza *et al*., 2023). Aluminum is a limiting

factor for many crops and is associated with excessive soil acidity that renders root development. It is a phytotoxic element that produces unfavorable effects in plants; however, the Al^{3+} content found in the soil of the present study is between 2.1 and 5 $mmol_c/dm^3$, which is low, according to Alvarez *et al*. (1999).

The rise of the contents of Al^{3+} and potential acidity ($H + Al^{3+}$) in the 0.2-0.4 m layer, which was also demonstrated by the multivariate analysis, indicates that the applied Ca (gypsum) and K_2O caused the displacement of the cationic Al^{3+} and H^+ ions from the layer of 0-0.2 to deeper soil layer. Thus, low gypsum and K_2O doses of 360 kg/ha or higher would affect soil chemical characteristics by the presence of Ca^{2+} and K^+ bases and move undesirable cations to deeper soil layers.

The B leaching potential is high (Thakur & Kumar. 2020), and the B leaching to the subsurface soil layers can be accentuated by soil texture. In the present study, such leaching was not observed. Despite a significant regression identified between gypsum doses and soil B at 0-0.2 m soil depth, the content ranged between only 0.21 and 0.26 mg/dm^3, which are within the low-level class (0.16-0.35 mg/dm^3) of soil B content (Alvarez *et al*., 1999). Thus, the gypsum dose effect could not even improve soil B content to a superior soil availability class. Plant biological effects are less likely to occur due to low B changes in soil. However, the better yield effects of applying gypsum and B sources are regularly reported in the literature (Ramya *et al*., 2022).

Calcium content increases linearly with gypsum doses in both soil layers (Figure 2A) and in the analysis of main components; these results corroborate with Caires *et al*. (2004) observed on corn and Nóia *et al*. (2014) on forage grass, who evaluated soil Ca levels in dissimilar conditions. The soil Ca^{2+} content accretions also corroborate the result found by Santos *et al*. (2020). Naturally, this soil Ca^{2+} content increase was caused by gypsum application since it contained about 18% Ca in its composition. Furthermore, Caires *et al*. (2004) also observed increasing Ca^{2+} content at a soil depth of 0-0.8 m with applying gypsum. These authors report 18 $mmol_c/dm^3$ in the 0.2-0.4 m layer after applying 3,000 kg/ha of gypsum to a dystrophic Red Latosol (Oxisol).

The effect of gypsum doses was also observed in the rise of the Ca/Mg ratio, which is logically explained by higher Ca^{2+} content in the soil after gypsum solubilization. However, the Ca/K ratio, whose average value was 8.17 in the 0-0.2 m soil layer and 4.83 in the 0.2-0.4 m soil layer, was unaffected by gypsum or K_2O factors. Despite applying both elements (Ca and K) by using gypsum and KCl, the Ca/K ratio was stabilized by adding both terms of the ratio Ca/K.

Soil K^+ is another soil base affected by the K_2O doses applied, which was also indicated in the analysis of main components. The initial soil K content in the 0-0.2 m layer was 3.53 $mmol_c/dm^3$, and even the application of 360 kg K_2O/ha, after the cultivation, was observed to diminish the content of this nutrient by 0.47 $mmol_c/dm^3$. This reduction in soil K content can be attributed to the high K extraction of the cauliflower plant in the 0-0.20 m soil layer (Castoldi *et al*., 2009; Charlo *et al*., 2021), up to 232.4 kg/ha of K. In addition, the K leaching to the 0.2-0.4 m layer must be considered a function of the soil texture in the experimental site (21% clay), which has little capacity to retain cations and the precipitation and irrigation that occurred during cauliflower cultivation.

A linear effect of fertilizer dose on soil K^+ content is a regular situation when using a highly soluble K^+ source (KCl). Araújo *et al*. (2012) also observed that the application of K doses (0, 50, 100, 200, and 400 kg K_2O/ha) to pumpkin on a dystrophic Red Latosol (Oxisol) presented a linear increase in soil K^+ content in the 0-0.2 m soil layer. The authors report 7.60 $mmol_c/dm^3$of soil K at a dose of 400 kg/ha of K_2O (initial soil K was 1.30 $mmol_c/dm^3$).

The effect of the K_2O factor on soil K^+ content in both soil layers was also observed in the reduction of the Mg/K ratio as the K_2O doses increased, which is logically explained by the increase in K^+ content. Soil basic cations, such as Ca^{2+}, Mg^{2+}, and K^+, have no ideal saturation ratio for crop development (Chaganti & Culman, 2018). Such saturation ratios should not be sought since no robust literature supports specific proportions; instead, plant nutrition management should focus on providing all nutrients in adequate levels for high crop performance and yield.

The effects of gypsum and K_2O on soil bases and the sum of bases (SB) are expected since both fertilizers are sources of such bases. This effect on SB was observed only by the gypsum factor and was especially strong in the topsoil layer evaluated, where the graph of the SB rose as the soil Ca and K also rose with the dose improvement. However, Costa *et al*. (2007) and Souza *et al*. (2012) did not observe significant effects of gypsum application (2,000 kg/ha) compared to the control (0 kg/ha of gypsum) on the SB in Red Latosols. The sum of bases is a parameter estimated by the sum of Ca^{2+}, Mg^{2+}, and K^+ contents in soil, and the gypsum addition was sufficient to change the SB in the first soil layer of the present study. However, only gypsum fertilization could not change such parameters in the same soil class as other studies (Costa *et al*., 2007; Souza *et al*., 2012).

The cation exchange capacity (CEC) is estimated by summing the SB and the soil Al^{3+} content. The effect of K_2O doses on CEC in the 0.2-0.4 m soil layer observed in the present study is most likely related to increased K^+ content and displaced Al^{3+} in the soil (Figures 3A and C). A high concentration of essential cations in the soil (Ca^{2+}, Mg^{2+}, and K^+) indicates a high CEC and, consequently, an increased soil fertility.

The S content observed in the 0-0.2 m soil layer is 99.78% higher than 28 mg/dm^3 (soil layer 0-0.2 m at 1,700 kg gypsum/ha) reported by Crusciol *et al*. (2014) while evaluating the productivity and fertility of sugarcane on a Red Latosol. The evaluation of vegetative bean growth and chemical attributes of Dystroferric Red Argisol found 49.71 mg/dm^3 in the same layer for treatment with 8,000 kg/ha of gypsum (Foloni *et al*., 2008), which is similar to this study. However, it is important to note that Foloni *et al*. (2008) used twice the maximum dose of gypsum in this study.

The S content observed in the 0.2-0.4 m soil layer is 60.57 mg/dm at 4,000 kg gypsum/ha, which is 110% higher than 28.9 mg/dm^3 (soil layer 0.2-0.4 m at 1,700 kg gypsum/ha) reported by Crusciol *et al*. (2014). The evaluation of the effects of increasing gypsum doses on wheat and soybean yield and soil chemical characteristics found 38.14 mg/dm^3 at 5,000 kg gypsum/ha in the 0.2-0.4 m layer of a clayey Latosol (Rampim *et al*., 2013), which is 59% lower than in this work.

The results observed by Foloni *et al*. (2008), Rampim *et al*. (2013), and Crusciol *et al*. (2014) were low compared to the high soil S contents in both evaluated soil layers of the present study. These low results were probably due to the low clay content in the soil on the experimental site, which contains few functional groups (iron and aluminum oxide) able to retain sulfate ions and consequently prevent their leaching to subsurface layers. Still, comparing S contents before the experiment, it is possible to notice high solubility of gypsum (2.04 g/L), which caused greater mobility of SO_4^{2-} in the soil profile and consequently elevated S contents in both soil layers.

The overall observed results in the present study indicate that applying gypsum and K_2O proved an interesting agricultural practice to improve soil nutritional status for the cauliflower crop (except for soil B at 0-0.2 m soil layer when gypsum is applied); however, the cauliflower productivity was only affected by potassic fertilization, probably due to the satisfactory original level of sulfur in the soil. Gypsum for horticultural crops is a viable alternative to reusing a low-risk industrial residue (Sultana *et al*., 2019), especially regarding the supply of Ca^{2+} and S contents in deep soil layers. Combined with potassic fertilization, gypsum to cauliflower should be positive for yield and soil improvements. Other benefits of the combined application of gypsum and potassic fertilization to cauliflower, such as high K^+ content in leaves and improved commercial head mass, were also highlighted by Charlo *et al*. (2021).

The soil parameters evaluated after cauliflower were influenced by gypsum and K_2O fertilization. Gypsum raises the soil calcium and sulfur content in both soil layers, 0-0.2 and 0.2-0.4 m depth. K_2O raises soil potassium content and potential acidity ($H^+ + Al^{3+}$) and decreases Mg/K ratio in both soil layers, 0-0.2 and 0.2-0.4 m depth. Micronutrients such as copper, iron, manganese, and zinc are not affected by gypsum or K_2O doses; gypsum's effect on boron content was minor. Cauliflower head productivity was affected by the potassic fertilization (15.93 t/ha cauliflower head production when 360 kg/ha of K_2O was applied) and presented no interference of gypsum dose mostly due to the adequate soil sulfur range for plant development.

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AUTHOR CONTRIBUTIONS

HCOC: conceptualization, investigation; JSMA: resources, conceptualization; EFAM: formal analysis; JLRTT: methodology, project administration; RC: visualization; MRFJ: supervision; EML: writing, review and edition.

STATEMENTS AND DECLARATIONS

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY

Data will be made available upon request to the corresponding author.

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