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Research Article

Lithothamnium Effects on Soil Attributes, Phosphorus Utilization Efficiency, and Grain Yield of Soybeans, Corn, and Common Bean

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Lithothamnium is a source of organic origin fertilizer that can be used to improve soil biochemical conditions and the initial development of plants and grain yield. This study aimed to evaluate the effect of Lithothamnium on initial soil chemical attributes and its effects on phosphorus (P) release (PUE—plant phosphorus use efficiency) and yield of soybean, corn, and common beans. Three experiments were conducted from 2020 to 2023 in a randomized block design with six replications. (1) Under greenhouse conditions, in the factorial scheme, with four doses of Lithothamnium with and without P, (2) under field conditions, in the factorial scheme with five calcium (Ca) doses × three sources of Ca, and (3) also, under field conditions, with a combination of four doses of Lithothamnium and four doses of P. The results of the experiment under greenhouse conditions showed that the increase in Lithothamnium doses provided to the soil a reduction in active and potential acidity very quickly (30 days) with a direct effect on the increase in clay activity (more negative charges). Besides, it increased the level of P and Ca in the soil and improved the amount of P and Ca absorbed by the soybean plants. Therefore, it showed the great efficiency of Lithothamnium in releasing P (from 13 to 30 ppm of P when increasing Lithothamnium rates). In the second experiment, it was concluded that Ca from Lithothamnium was the most efficient source for the initial chemical conditions in the furrow and that it provided significant increments in grain yield and P and Ca contents in the petiole of soybean plants. After these results, six field experiments showed significant increases in the efficiency of PUE in common bean, soybean, and corn crops (63% on average). Lithothamnium has become an indispensable technology to provide greater productive efficiency for crops.

1. Introduction

Due to the high rate of phosphorus (P) fixation in tropical soils, its use by crops is very low, ranging from 5 to 25% [1, 2]. According to Vermeiren et al. [3], practically all P is retained in the solid phase when phosphate fertilizers are applied to the soil. This is because of the reaction with silicate clays and the occurrence of many hydrated oxides, mainly linked to iron and aluminum, which fix P. However, when calcium is abundant (Ca) in the sowing furrow, better conditions for crop development can be created [4]. Nascente and Cobucci [5] reported that the application of sources of P together with calcium (single superphosphate; MAP + $CaNO_3$; MAP + $CaCO_3$) in the sowing furrow significantly increased common bean grain yield. In this sense, Ca and P are very important to crop root development, which creates better conditions for the plants to uptake more water and nutrients from the soil [1]. Besides, the use of Ca in limestone sources increases Ca levels in the soil and increases pH, which improves P in the soil [5].

Phosphorus use efficiency (PUE) in an agricultural production system can be defined as the ratio of the mass of P harvested from agricultural products (P yield) to the mass of total P inputs into this system in a given period [6]. According to Chen and Graedel [7], PUE in agriculture refers to the conversion ratio of total P input into plant exports (harvested crops). Therefore, PUE in agricultural production systems is an important indicator to measure the situation of P management in agriculture and its impacts on food security and environmental conservation [8].

The term granulate is used to designate the set of small grains gathered and cemented together, constituting a larger body whose aspect may be homogeneous or not. At the bottom of the ocean, marine granules are formed from lithoclast sands and gravels, calcareous sands, algae, and others [9]. When the marine granulates are called bioclastic, it means that it has a carbonate composition and are essentially made up of materials derived from living organisms, such as calcareous algae, mollusks, bryozoans, benthic foraminifera, and quartz [10], giving to this material a higher pKa (negative value of the logarithm of the dissociation constant of acid and means how fast an acid can dissociate) than mineral limestone, which will provide greater neutralization power.

In the composition of the bioclastic granules, the group of calcareous algae belonging to the phylum Rhodophyta, class Rhodophyceae, order Corallinales, family Hapalidiaceae, stands out, which has 34 genera and from 300 to 500 species [11]. The most extracted calcareous algae are of the genus Lithothamnium. Such organisms have a calcareous appearance, absorbing calcium and magnesium carbonate as calcite, representing 80% to 90% of their biomass [12].

Thus, Lithothamnium is found on the French, English, and Irish coasts and, in large quantities, can be used to correct acidic and/or calcium-deficient soils [13, 14]. The occurrence of these algae has also been described in Australia [15], Korea [16], Mexico [17], and Chile [16]. In Brazil, deposits of calcified algae are found from the Amazon Region to the south of Rio de Janeiro, extending about 4,000 km, and it grows in depths of 10 to 40 meters [18]. This fossilized seaweed can accumulate nutrients between its cell walls and enhances all physiological processes beneficial to plant and animal development [19].

The reaction of Lithothamnium in the soil is very fast; in their studies, Chaves et al. [20] applied limestone to the soil 60 days before corn sowing and Lithothamnium only 24 hours before and obtained the expected effect of pH reduction and supply of Ca and magnesium (Mg). The use of Lithothamnium can be an important alternative for improving soil biochemical conditions and providing better plant development in the early stages. This material is abundant in many country coasts [13–17]. In a sustainable way, instead of trash, it can be used to improve plant development and grain yield. However, there are only a few studies about using Lithothamnium in crops.

Soybean (*Glycine max*), corn (*Zea mays*), and common bean (*Phaseolus vulgaris*) are the main crops cultivated in Brazilian savannas, which have problems with soil acidity [1]. Therefore, research should be done to create options to solve the problem of soil acidity to improve plant development and grain yield. Besides, Brazil is the fourth largest consumer of fertilizers in the world, with 8% of global fertilizer consumption, of which 80% of these fertilizers are imported; therefore, this action corroborates the National Fertilizer Plan in Brazil, which seeks to study alternative sources of fertilizers for agriculture [21]. However, there are still few studies on using this alga in developing crops. This study aimed to evaluate the effect of Lithothamnium on initial soil pH and its effects on phosphorus (P) release (PUE—plant phosphorus use efficiency) and yield of soybean, corn, and common beans.

2. Material and Methods

2.1. Experiment 1—Greenhouse. The experiment was conducted under greenhouse conditions from Nov 2022 to Feb 2023 at the Cobucci Agro experimental station in Hidrolândia-GO. The experimental design was completely randomized, arranged in a 2×4 factorial, with six replications. The treatments consisted of a combination of two phosphate fertilizations (1. without P, and 2. 100 kg of P_2O_5 (monoammonium phosphate (MAP) was used as source, which has 10% N and 50% P_2O_5)) with four doses of Lithothamnium (0, 100, 150, and 300 kg ha^{-1}). According to Ernani et al. [22], applying correctives and phosphate fertilizers on the soil surface changes the chemical composition of the solid phase only in the superficial layer of 0–2 cm in the first 30 days after application. Therefore, we consider the calculation of the amount of soil in 1 ha, considering 2 cm of soil and not 20 cm. Therefore, 1 ha of soil (2 cm) has 200,000 kg of soil. As we applied the treatments with five replications, we mixed the fertilizer in 10 kg of soil with 5 g, 7.5 g, and 15 g of Lithothamnium for doses of 100, 150, and 300 kg ha^{-1}, respectively. After mixing in a plastic bag, 2 kg of the mixture was placed in each pot. The N contents were corrected so that all plots received the same amount of the nutrient, varying only the amount of phosphorus according to each treatment. Pots filled with 2 kg of dry and not crushed soil were used to cultivate soybean cultivar Nidera 7902, using six seeds per pot. Lithothamnium was applied using the commercial product Primaz® (32% Ca and 2% Mg).

At 30 days after soybean germination, the plants were harvested. Then, the following was evaluated: (1) pH (active acidity), (2) H + Al (potential acidity), (3) clay activity ((cation exchange capacity × 100)/(% of clay content)), (4) remaining P (P that was added to the soil), (5) P content in the soil, and (6) P content uptaked by soybean plants.

2.2. Experiment 2—Field. Experiments in no-tillage areas in the 2021/2022 crop season were conducted in four locations: (1) Nova Era farm, in São João da Aliança, Goiás state; (2) Santa Fé farm, in Santa Helena de Goiás, Goiás state; (3) São

Miguel farm—Bom Futuro, in Campo Verde, Mato Grosso state; and (4) Gaio farm, Novo Planalto, Goiás state. The sites had a clay loam (kaolinitic, thermic Typic Haplorthox, and, according to Brazilian classification, Latossolo Vermelho distrófico), acidic soil in gently undulating topography. Before the installation of the experiments, soil samples were collected, and chemical analyses were conducted in each location (Table 1). According to the Koppen classification, the local climate was classified as Aw-type (tropical savannah), mesothermal.

The experimental design used was randomized blocks arranged in a 5×3 factorial scheme with six replications. The treatments consisted of five doses of Ca (0, 13, 19, 26, and 38 kg·ha^{-1}) applied in the sowing furrow × three sources of Ca ((1) Ca-Lithothamnium, (2) Ca-$CaCO_3$, and (3) Ca-$CaSO_4$). The calcium sources were applied in the sowing furrow mixed with the MAP fertilizer applied in 180 kg·ha^{-1} (90 kg·ha^{-1} of P_2O_5). Lithothamnium was applied using the commercial product Primaz® (32% Ca and 2% Mg). The dimensions of the plots were 2.0 m wide (four rows) and 10 m long, totaling 20 m^2. The useful area comprised two central rows of 4 m in each plot, disregarding 1.0 m on each side. The soybean cultivar Nidera 7902 was used, using 16 seeds per meter and a row spacing of 0.45 m. Plants were irrigated periodically and managed to develop free from attack by pests, diseases, and weeds.

2.3. Experiment 3—Field. Experiments in no-tillage areas in the 2020/2021 crop season were conducted in three locations: (1) Nova Era farm, São João da Aliança, Goiás state; (2) Bonsucesso farm, in Hidrolândia, Goiás state; and (3) Santa Efigênia farm, in Jaborandi, Bahia state. The sites had soils classified as Latossolo Vermelho-Amarelo distrófico with clayey loam (São João da Aliança and Hidrolândia) and sandy loam (Jaborandi-BA) textures. Before the installation of the experiments, soil samples were collected, and chemical analyses were conducted in each location (Table 2). According to the Koppen classification, the local climate was classified as Aw-type (tropical savannah), mesothermal.

Two experiments were conducted for each crop. Thus, the soybean experiments were conducted in soil with sandy texture (12% clay) and medium texture (33% clay), common bean in the off-season and winter, and corn in the summer and off-season. In all experiments, the experimental design used was randomized blocks arranged in a 4×4 factorial scheme with six replications. The treatments were composed of a combination of four doses of P_2O_5 (0, 40, 80, and 120 kg·ha^{-1}) with four doses of Lithothamnium (0, 40, 60, and 80 kg·ha^{-1}). The phosphorus source was the MAP fertilizer. The N contents were corrected so that all plots received the same amount of the nutrient, varying only the amount of phosphorus according to each treatment. Lithothamnium was applied using the commercial product Primaz® (32% Ca and 2% Mg) and mixed with MAP at sowing. The dimensions of the plots were 2.0 m wide (four rows) and 10 m long, totaling 20 m^2. The useful area of each plot was composed of two central rows of 4 m, disregarding 1.0 m on each side.

2.4. Crop Management. The spacing between rows was 0.50 m, and the seed density per meter was 8 seeds in beans, 12 seeds in soybeans, and 3 seeds in corn. In the common bean experiments, the doses of N (urea) and K_2O (potassium chloride) in all treatments were 105 and 60 kg·ha^{-1}, respectively, and the N was split with the application of 20 kg·ha^{-1} of N at sowing and the remainder at the V4 vegetative stage (four fully open trifoliate leaves). For corn, it was 130 and 80 kg·ha^{-1}, respectively, with N being split with the application of 20 kg·ha^{-1} of N at sowing and the remainder at the V4 vegetative stage (four fully open leaves). For soybeans, only 60 kg·ha^{-1} of K_2O was applied by broadcast right after sowing.

3. Assessments

3.1. Evaluation of P and Ca Contents in the Sap of the Petiole and Leaf Blade. Petioles and leaf blades of soybean plants were sampled 30 days after plant emergence (DAE) to determine the Ca and P content in the sap of these botanical organs, according to the methodology described by [23, 24]. Briefly, in 20 soybean plants, two leaves with petioles were randomly selected from each plot. Soybean petioles and leaves were separated. Petioles were cut and pressed, and the sap was immediately measured.

3.2. Phosphorus Use Efficiency. Phosphorus use efficiency was calculated by the yield of a given treatment minus the yield of the control treatment (without phosphorus application) divided by the amount of phosphorus applied [25]. With this, we had the yield of the crop per kilogram of phosphorus applied ((Yt − Yc)/Pa), where Yt is yield of a given treatment, Yc is yield of the control treatment (no P application), and Pa is amount of P applied.

3.3. Grain Yield and Yield Components. For the evaluation of the yield components (number of pods or ears/plant, number of grains/pod or grains/ear, and 100-grain weight), ten plants were randomly collected in each plot. The grain yield of all crops (130 g·kg^{-1} of moisture) was also evaluated by harvesting in the useful area of each plot.

3.4. Statistical Analysis. In experiment 1, statistical analysis of the data and ANOVA was conducted, and when a significant effect was observed, regression analysis was conducted. In experiments 2 and 3, data were subjected to analysis of variance, and when the F-test was significant, regression analysis was performed. With the grain yield data of the crops as a function of P_2O_5 doses for each Lithothamnium dose for each crop, the phosphorus use efficiency was calculated. The area under the curve was also calculated for each crop for each phosphorus dose range. Additionally, the efficiency of using phosphorus at dose zero was considered 100%. At the other doses, the increase in this efficiency concerning treatment with dose zero was evaluated, also in percentage.

Table 1: Chemical and physical properties of the soils (0–20 cm layer) where the experiments were installed, 2021.

2021-Campo Verde-MT								
P	K		Ca		Mg	S	SOM1	pH (H2O)
-------mg dm^{-3}------			----cmolc dm^{-3}----			mg dm^{-3}	g dm^{-3}	
30.0	60		3.4		0.6	5.7	29.00	5.4
Cu	Fe	Mn		Zn	B	Clay	Silt	Sand
	----------------------mg dm^{-3}-----------------------						--------------------g kg^{-1}-----------------	
2.4	100	23.9		12.00	0.33	300	200	500
2021-Novo Planalto-GO								
P	K		Ca		Mg	S	SOM1	pH (H2O)
-------mg dm^{-3}------			----cmolc dm^{-3}----			mg dm^{-3}	g dm^{-3}	
22.0	100		2.4		0.7	10.7	19.00	5.2
Cu	Fe	Mn		Zn	B	Clay	Silt	Sand
	-----------------------mg dm^{-3}----------------------						--------------------g kg^{-1}-----------------	
6.5	54	53.6		7.00	0.23	170	200	630
2021-São João da Aliança-GO								
P	K		Ca		Mg	S	SOM1	pH (H2O)
-------mg dm^{-3}------			----cmolc dm^{-3}----			mg dm^{-3}	g dm^{-3}	
62.0	98		2.9		1.1	13.6	22.00	5.5
Cu	Fe	Mn		Zn	B	Clay	Silt	Sand
	------------------------mg dm^{-3}---------------------						-----------------g kg-1------------------	
7.6	111	45.5		45.00	0.34			

[1]Soil organic matter.

Table 2: Chemical and physical properties of the soils (0–20 cm layer) where the experiments were installed, 2020.

2020-Hidrolândia-GO							
P	K	Ca		Mg	S	SOM1	pH (H2O)
-------mg dm^{-3}------		----cmolc dm^{-3}----			mg dm^{-3}	g dm^{-3}	
30.0	60	3.4		0.6	5.7	29.00	5.4
Cu	Fe	Mn	Zn	B	Clay	Silt	Sand
	----------------------mg dm^{-3}------------------------					----------------g kg^{-1}----------------	
2.4	100	23.9	12.00	0.33	300	200	500
2020-Jaborandi-BA							
P	K	Ca		Mg	S	SOM1	pH (H2O)
-------mg dm^{-3}------		----cmolc dm^{-3}----			mg dm^{-3}	g dm^{-3}	
22.0	100	2.4		0.7	10.7	19.00	5.2
Cu	Fe	Mn	Zn	B	Clay	Silt	Sand
	------------------------mg dm^{-3}----------------------					---------------g kg^{-1}----------------	
6.5	54	53.6	7.00	0.23	170	200	630
2020-São João da Aliança-GO							
P	K	Ca		Mg	S	SOM1	pH (H2O)
-------mg dm^{-3}------		----cmolc dm^{-3}----			mg dm^{-3}	g dm^{-3}	
62.0	98	2.9		1.1	13.6	22.00	5.5
Cu	Fe	Mn	Zn	B	Clay	Silt	Sand
	-------------------------mg dm^{-3}----------------------					---------------g kg^{-1}------------------	
7.6	111	45.5	45.00	0.34			

[1]SOM: soil organic matter.

4. Results and Discussion

4.1. Experiment 1—Greenhouse. Based on the results, it was possible to verify that the increase in Lithothamnium doses provided a reduction in active and potential acidity, a greater increase in clay activity (more negative charges), greater P remaining, higher P contents by the Mehlich extractor, higher Ca content in the soil, and a higher amount of P absorbed by soybean plants (Figure 1). Lithothamnium presents a fast reaction in the soil, releasing organic substances, calcium and carbonates, and improving the biochemical conditions of the soil much faster than mineral limestone [20]. This occurs because the Ca-Lithothamnium carbonate solubilization reaction has a higher pKa than mineral limestone (due to the mineral constitution of this Ca carbonate). Thus, with the application of seaweed in the planting furrow, an increase in pH was obtained, a reduction in potential acidity (H + Al), and an increase in clay activity. With the increase in pH, increases in P contents in the soil and the plant were expected [1]. Also, increments were observed in the remaining P, P content in the soil, and P absorbed by the soybean plants.

In acidic or moderately acidic soils, such as the soil of the present study (pH 4.74), the iron and aluminum oxides present in the clays present preferentially with positive charges, thus being capable of retaining various types of anions on their surface, predominance of phosphate ions [25]. Thus, it is expected that the application of agricultural correctives reduces the positive charges in the soil and, therefore, increases clay activity, as observed in the present experiment.

Remaining phosphorus measures the amount of P remaining in the equilibrium solution in response to a P concentration added to the soil. Thus, the more positive charges, the more fixed the P and the smaller the remaining P. With the increase in Lithothamnium doses, there was a reduction in the positive charges in the soil (increase in pH and reduction in potential acidity). With that, the remaining P increased on a linear scale.

The increase in Lithothamnium doses provided linear increases in P contents in the soil, evaluated by the Mehlich extractor. This occurred because Lithothamnium improves soil chemical conditions much faster, since the soil evaluation was carried out 30 days after the application of Lithothamnium. With this, it can be inferred that applying Lithothamnium in the soil provides higher P levels in the soil in a short period, in the case of the present experiment, 30 days. As observed, the increase in P availability in the soil favors greater P uptake by soybean plants. In studies conducted with common beans, Nascente and Cobucci [5] also observed increases in P levels in plants due to the increase in P levels in the soil. The authors attributed the result to the reduction in P fixation by Fe and Al oxides. According to Fageria and Nascente [1], P is highly fixed in Cerrado soil; however, when applying limestone, this fixation is reduced, increasing the P availability in the soil, and the plants can uptake more P.

4.2. Experiment 2—Field. In the average of the four locations where the experiments were conducted, it was found that the Ca-Lithothamnium source was more efficient in providing significant increases in soybean grain yield (Figure 2). As observed in experiment 1, applying this fertilizer increases P levels in the soil, which favors the initial development of plants with positive effects on the crop grain yield. Thus, it is likely that the application of Lithothamnium in the sowing furrow caused the precipitation of Al and Fe in the forms of $AlOH_3$ and $FeOH_3$ and provided increased P availability at the beginning of crop development only in the sowing furrow and led to better conditions for plant development. Nascente and Cobucci [5] also observed significant increases in common bean grain yield due to increased application of lime in the sowing row of the crop. The authors attributed the result to the probable increase in the availability of P for the plants at the initial stage of development.

It was also observed that with the increase in Ca-Lithothamnium doses, there was an increase in the levels of P (Figure 2) in the sap of the plant and Ca in the sap and blade of the soybean leaves. Notably, the values obtained with Ca-Lithothamnium were higher than those obtained with $CaCO_3$, indicating that the former provides faster reactions in the soil than the latter. This occurs because the carbonate solubilization reaction of Ca-Lithothamnium has a higher pKa, giving the former greater neutralizing power and reaction speed. According to Cavalcanti 2011 [10], Lithothamnium, which is called bioclastic, is essentially made up of materials derived from living organisms, such as calcareous algae, mollusks, bryozoans, benthic foraminifera, and quartz that provide fast dissolution in the soil. Chaves et al. [20] showed that Lithothamnium applied 24 hours before sowing plants provided the same effect of pH reduction and supply of Ca and Mg when applied limestone 60 days before sowing plants.

4.3. Trial 3—Field. The use of Lithothamnium increased the phosphorus use efficiency in all crops (soybean, common bean, and corn) (Tables 3, 4, and 5). The PUE indicates the conversion of applied P into yield by the crops; that is, the higher the PUE, the greater the grain yield of the crop per unit of phosphorus applied to the soil [8]. Thus, it appears that it is likely that the use of Lithothamnium has provided greater availability of P in the soil, reducing the fixation of the P applied, as the results in experiments 1 and 2, and favoring its absorption by the plants, which resulted in greater grain yield in the studied crops (Figures 3, 4, and 5). P, when applied, can be fixed by clay minerals rich in Fe and Al and become unavailable to plants [1].

In the medium-textured soil, the dose of 60 kg ha^{-1} of Lithothamnium provided the highest PUE, and in the sandy-textured soil, the PUE was much higher. According to Valladares et al. [25], clayey soils have more positive charges than sandy soils. Thus, they can retain various anions, such as phosphate, which is why higher P levels are needed in clayey soils than in sandy soils; this leads to lower PUE values in clayey soil than in sandy soil.

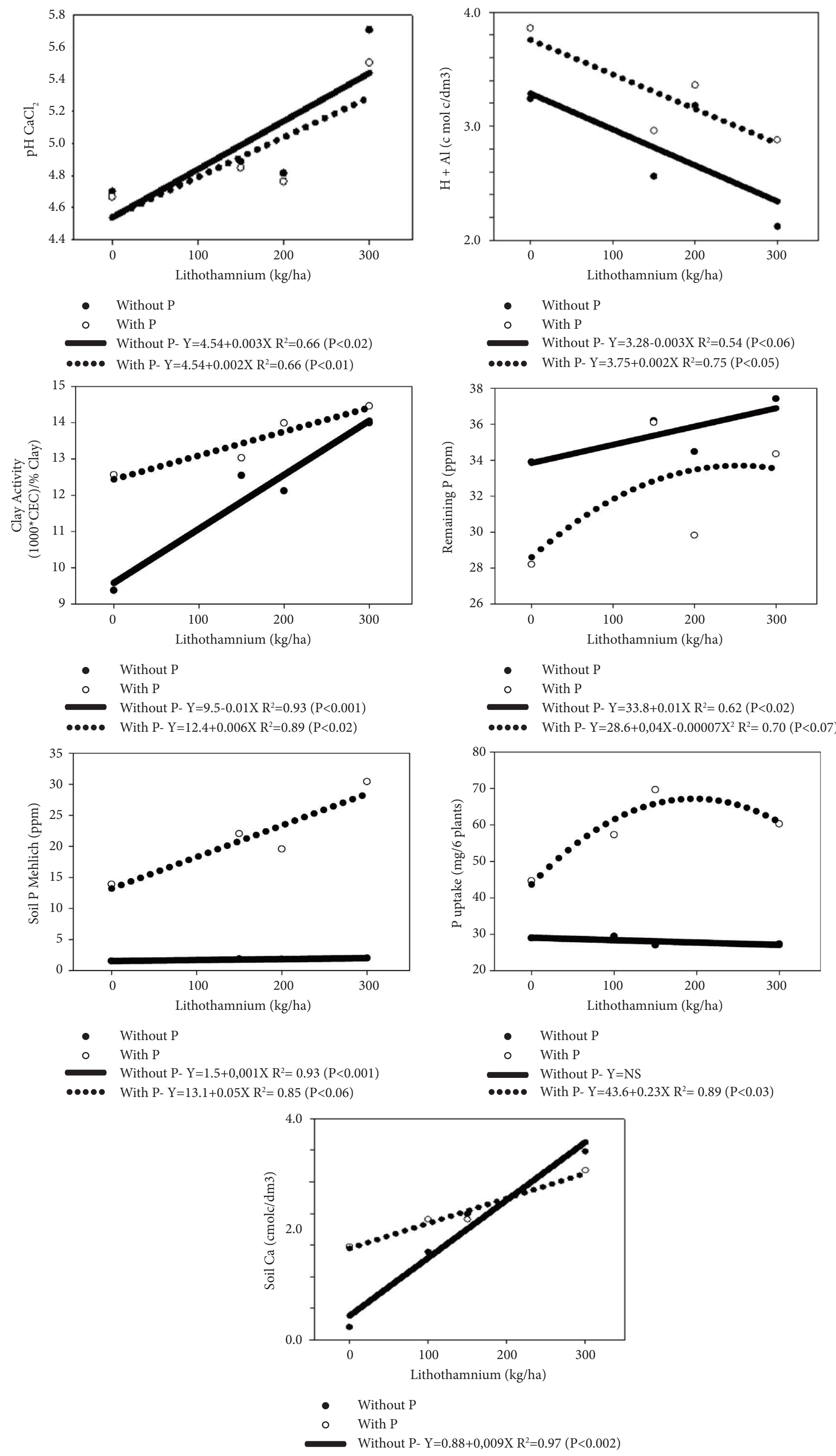

Figure 1: Soil and soybean plant attributes according to the phosphorus fertilization and Lithothamnium doses.

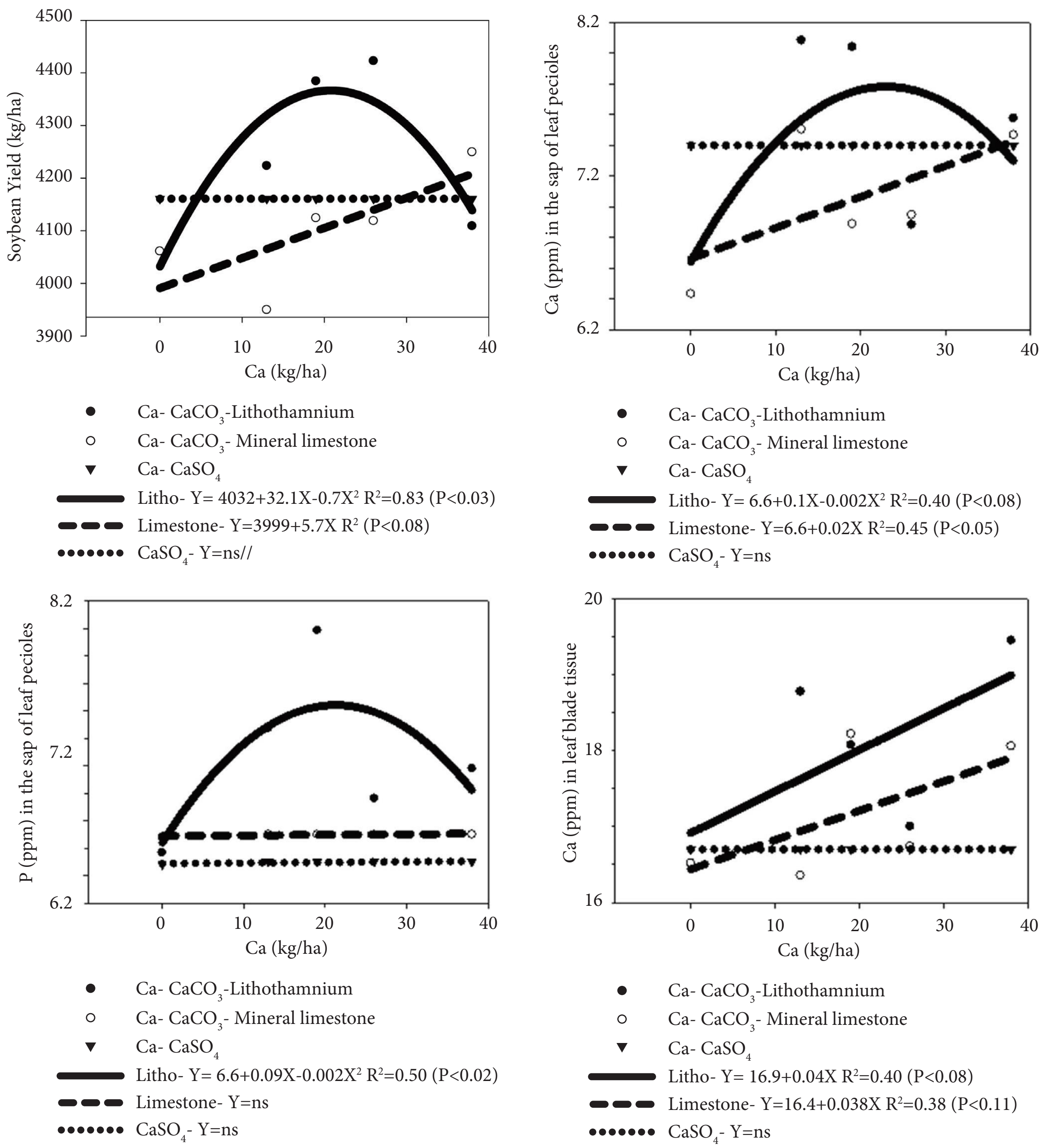

Figure 2: Soybean yield (kg ha^{-1}), P and Ca content (ppm) in the sap of soybean leaf petioles (30 days after emergence), and Ca content (ppm) in the blade tissue of soybean leaves (30 days after emergence) according to the sources and doses of Ca applied in the planting furrow.

In the common bean cultivated in the second harvest, depending only on rainwater, grain yield was low, and there was no interaction between the factors (Figure 4), so there was only an effect of doses of Lithothamnium. Possibly, only the P made available in the soil by the application of Lithothamnium was sufficient to provide greater yield gains for the crop. Studies explain the low or null response of P doses in the second crop, as drought periods usually occur and water availability for the crop is low, resulting in low grain yield [26]. Miranda et al. [27] tested three doses of phosphorus fertilization (250, 500, and 1000 kg ha^{-1} of P_2O_5) and two irrigation depths, one considered ideal (426 mm) and another with restricted water (338 mm), applied over the cycle of bean crop in the dry season. The authors observed that bean production increased with phosphorus fertilization at both irrigation depths and that the restricted irrigation depth promoted drastic reductions in grain yield in all treatments, regardless of the fertilizer used. Thus, even though the conditions were not adequate for the full development of the crop, the PUE value of the treatments with the application of Lithothamnium was much higher than the control treatment (Table 4). Thus, the phosphorus use efficiency was increased with the Lithothamnium application, which leads to greater savings for the producer, who achieves greater P efficiency with the appropriate dose for the crop.

Table 3: Regression equations and area under the curve for phosphorus use efficiency (PUE) of soybean according to Lithothamnium doses.

Lithothamnium doses kg ha^{-1}	Equation	Area under the curve (integral of the equation) Range of P_2O_5 kg ha^{-1} 40–60	60–80	80–100	100–120	Sum	%
Soybean—area with a sandy texture							
0	$Y = 1.26 + 0.21X - 0.0016X^2$ $R^2 = 0.50$ ($P < 0.10$)	163	174	159	118	614	100
40	$Y = 1.34 + 0.26X - 0.0019X^2$ $R^2 = 0.57$ ($P < 0.09$)	197	213	159	118	687	112
60	$Y = 2.54 + 0.48X - 0.0039X^2$ $R^2 = 0.54$ ($P < 0.11$)	333	338	282	160	1113	181
80	$Y = 2.26 + 0.69X - 0.0053X^2$ $R^2 = 0.75$ ($P < 0.06$)	469	492	430	283	1674	273
Soybean—area with a medium texture							
0	$Y = 1.24 + 0.39X - 0.0033X^2$ $R^2 = 0.77$ ($P < 0.04$)	249	245	189	81	764	100
40	$Y = 2.19 + 0.49X - 0.0041X^2$ $R^2 = 0.64$ ($P < 0.06$)	328	328	263	131	1050	137
60	$Y = 0.85 + 0.45X - 0.0034X^2$ $R^2 = 0.90$ ($P < 0.01$)	297	316	280	190	1083	142
80	$Y = 0.35 + 0.19X - 0.0015X^2$ $R^2 = 0.90$ ($P < 0.02$)	123	128	109	66	426	56

The regression equations refer to the calculation of the PUE, kilograms of soybean grains per kilogram of P_2O_5.

Table 4: Regression equations and area under the curve for phosphorus use efficiency (PUE) of common bean according to Lithothamnium doses.

Lithothamnium doses kg ha^{-1}	Equation	Area under the curve (integral of the equation) Range of P_2O_5 kg ha^{-1} 40–60	60–80	80–100	100–120	Sum	%
Common bean—off-season							
0	$Y = 0.19 + 0.038X$ $R^2 = 0.96$ ($P < 0.003$)	41	57	72	87	257	100
40	$Y = 0.97 + 0.23X - 0.0017X^2$ $R^2 = 0.66$ ($P < 0.11$)	168	181	166	124	639	249
60	$Y = -0.04 + 0.18X - 0.001X^2$ $R^2 = 0.99$ ($P < 0.002$)	128	152	160	152	592	230
80	$Y = 0.68 + 0.12X - 0.0008X^2$ $R^2 = 0.62$ ($P < 0.12$)	98	112	112	99	421	164
Common bean—winter (irrigated)							
0	$Y = 1.6 + 0.33X - 0.0026X^2$ $R^2 = 0.58$ ($P < 0.08$)	237	247	215	142	841	100
40	$Y = 1.1 + 0.42X - 0.0033X^2$ $R^2 = 0.82$ ($P < 0.03$)	277	288	245	151	961	114
60	$Y = 2.12 + 0.5X - 0.004X^2$ $R^2 = 0.66$ ($P < 0.05$)	334	337	275	147	1093	130
80	$Y = 0.81 + 0.27X - 0.0021X^2$ $R^2 = 0.79$ ($P < 0.07$)	179	187	160	100	626	74

The regression equations refer to the calculation of the PUE, kilograms of common bean grains per kilogram of P_2O_5.

Table 5: Regression equations and area under the curve for phosphorus use efficiency (PUE) in corn as a function of Lithothamnium doses.

Lithothamnium doses kg ha^{-1}	Equation	Area under the curve (integral of the equation) Range of P_2O_5 kg ha^{-1} 40–60	60–80	80–100	100–120	Sum	%
Corn—summer							
0	$Y = -1.52 + 0.69X - 0.0046X^2$ $R^2 = 0.88$ ($P < 0.07$)	435	485	473	390	1783	100
40	$Y = -4.57 + 0.95X - 0.0063X^2$ $R^2 = 0.63$ ($P < 0.10$)	527	600	572	444	2143	120
60	$Y = -1.15 + 1.22X - 0.0088X^2$ $R^2 = 0.97$ ($P < 0.04$)	771	835	732	539	2877	160
80	$Y = 3.83 + 1.32X - 0.011X^2$ $R^2 = 0.80$ ($P < 0.07$)	829	861	641	304	2635	148
Corn—off-season							
0	$Y = 1.22 + 1.06X - 0.0073X^2$ $R^2 = 0.96$ ($P < 0.01$)	694	768	712	536	2710	100
40	$Y = 0.83 + 1.18X - 0.0084X^2$ $R^2 = 0.88$ ($P < 0.07$)	774	841	784	584	2983	110
60	$Y = -4.96 + 1.70X - 0.0134X^2$ $R^2 = 0.89$ ($P < 0.10$)	1117	1150	981	582	3830	141
80	$Y = 6.64 + 1.66X - 0.0135X^2$ $R^2 = 0.68$ ($P < 0.11$)	1088	1134	952	494	3668	135

The regression equations refer to the calculation of the PUE, kilograms of corn grains per kilogram of P_2O_5.

On the other hand, in irrigated common beans, grain yield was much higher (above 4,600 kg·ha^{-1}) at the dose of 60 kg ha^{-1} of Lithothamnium combined with 70 kg·ha^{-1} of P_2O_5 (Figure 4). At this dose of Lithothamnium, the PUE had the highest value, 30% higher than that of the control (Table 4). With the lack of irrigation, the plant reduces growth, absorbs less nutrients, and decreases grain yield. Torres et al. [28] showed that an irrigation depth of 100% provided higher bean grain yields

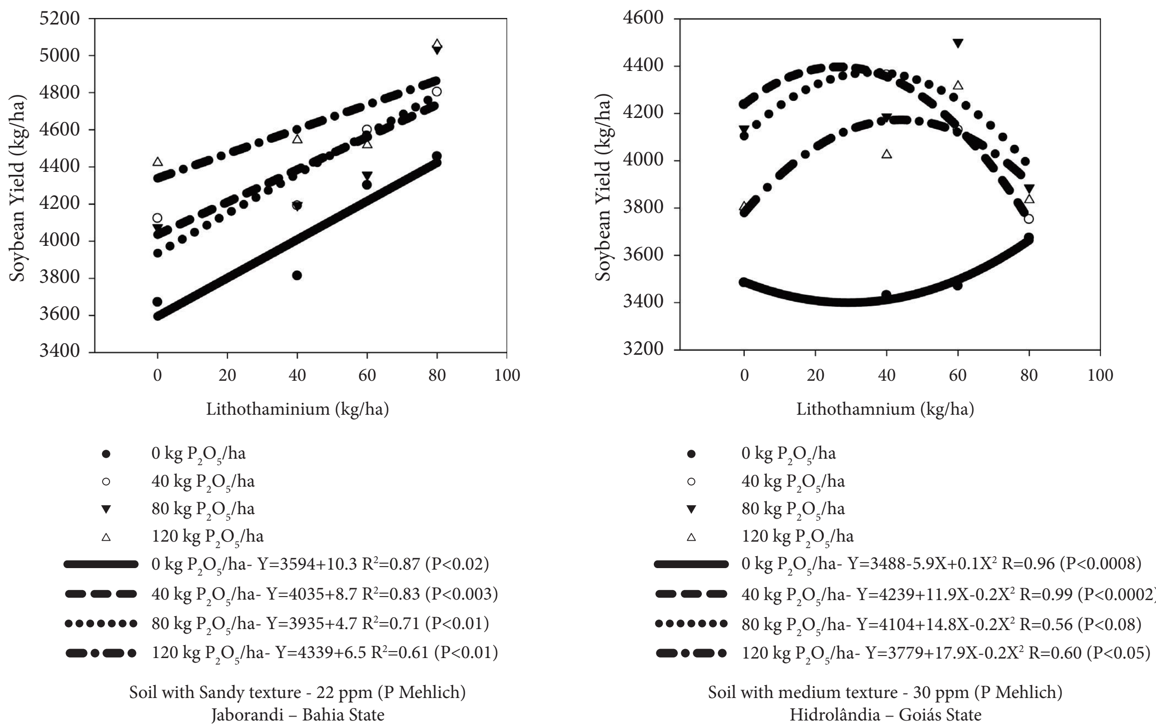

Figure 3: Soybean grain yield according to P_2O_5 doses (kg ha^{-1}) in each Lithothamnium dose.

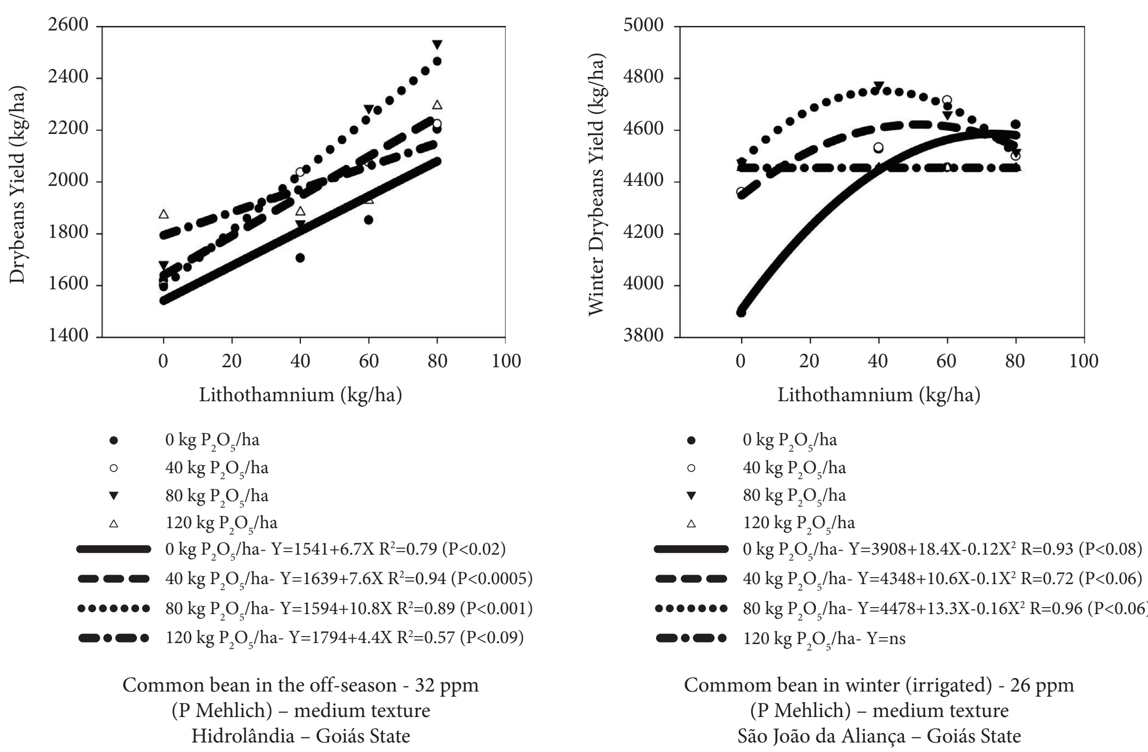

Figure 4: Common bean grain yield according to P_2O_5 doses (kg ha^{-1}) in each Lithothamnium dose.

than water depths of 40, 60, and 80%. Thus, it can be inferred that common bean plants developed better under irrigated conditions and absorbed more phosphorus, resulting in higher grain yield. In this sense, using Lithothamnium is important to provide greater availability of P in the soil for the plants to absorb and lead to greater grain yield, as observed by the PUE value. Limitations in the P availability at the beginning of the vegetative cycle can result in restrictions in development, from

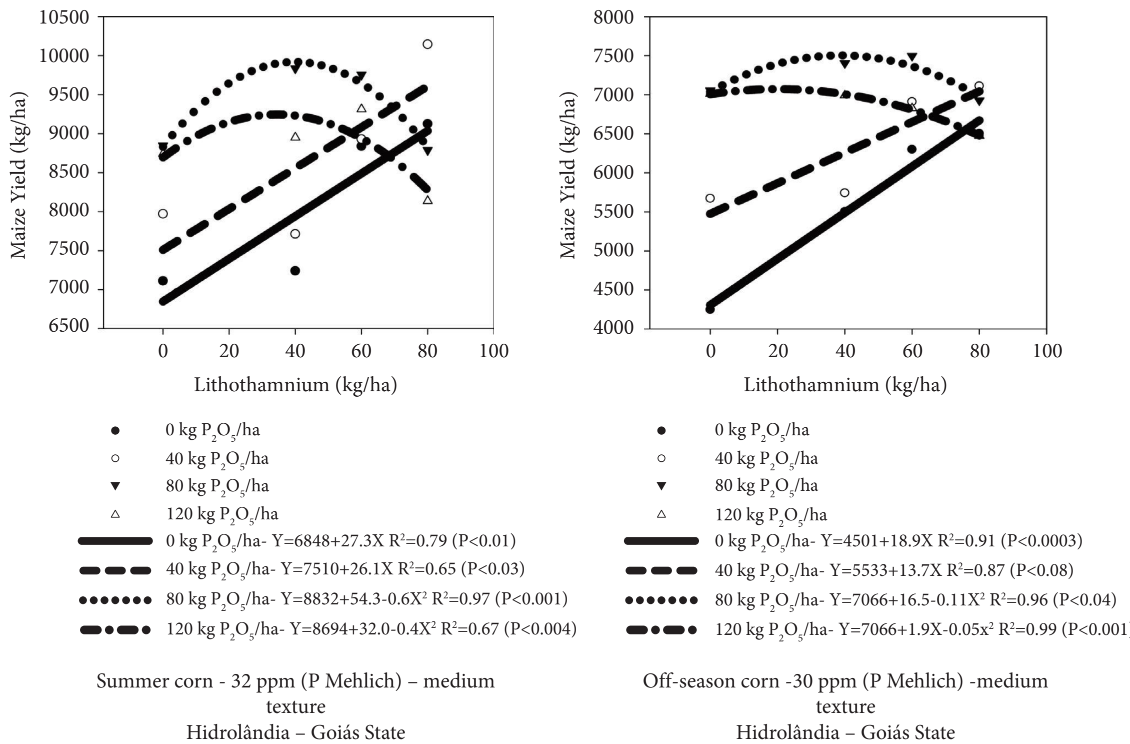

Figure 5: Corn grain yield according to P_2O_5 doses (kg ha^{-1}) in each Lithothamnium dose.

which the plant does not recover later, even increasing the supply of P to adequate levels [29]. In this sense, as observed in the previous experiment, using Lithothamnium leads to higher *P* values in the initial stage of plant development, resulting in greater development and yield, as observed in the present experiment.

In the corn crop, an interaction was also observed between doses of litho and phosphorus with higher yields in the summer, a time of greater precipitation (Figure 5). The greater availability of P in the soil by applying Lithothamnium and P_2O_5 doses provided significant increases in corn yield in both crop seasons. The PUE was higher at the dose of 60 kg ha^{-1} of Lithothamnium in both crop seasons (Table 5). Identifying the P dose that provides its greatest efficiency according to the Lithothamnium dose is important to avoid excessive or insufficient fertilization. It reduces fertilizer costs and environmental contamination and increases crop yield and producer profitability. Defining and estimating PUE in crops and production systems is important for better agricultural P management [30, 31].

4.4. Final Considerations. Based on the results obtained in the three experiments, it appears that the use of Lithothamnium can be strategic to increase P levels in the sowing furrow, causing a rapid improvement in soil chemical conditions and P levels in the sowing furrow. With this, adequate conditions are created for the initial development of the plants with positive effects on the grain yield of the crops. Lithothamnium increased the grain yield of the evaluated crops and P and Ca contents in the plants. Finally, it was found that the use of Lithothamnium increased the phosphorus use efficiency in soybean, common bean, and corn crops, indicating a more efficient use of the nutrient with the useful Lithothamnium location. It is also worth mentioning that Lithothamnium is abundant on the Brazilian coast and can be an alternative source of plant nutrients, helping Brazil reduce external dependence on fertilizers.

5. Conclusion

Under controlled conditions, it was found that up to 30 days, the increase in Lithothamnium doses provided a reduction in active and potential acidity, a greater increase in clay activity, greater P remaining, greater P (Mehlich) and Ca in the soil, and a greater amount of P and Ca absorbed by soybean plants. These results already indicated Lithothamnium's efficiency in increasing nutrient use efficiency.

After this initial trial, field experiments were conducted in four locations to confirm the data found under controlled conditions. In these experiments, it was found that the applications of Lithothamnium calcium sources in the sowing furrow provided significant increases in grain yield, and P and Ca contents in the petiole of soybean plants. A third set of experiments (six experiments) was carried out in the field with different species and environmental conditions to evaluate the P use efficiency in soils with sandy and medium texture, in common beans in the off-season and winter, and in corn cultivated in summer and off-season.

Lithothamnium is a source of organic origin fertilizer that can be used to improve the initial development of plants and lead to higher crop yields. Besides, it is important to test the Lithothamnium in other conditions and with other crops to confirm the good results achieved in our study.

Data Availability

The data used to support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Ethical Approval

Adriano Stephan Nascente, Tarcísio Cobucci, and Marco Araujo maintained the integrity of the research and its presentation and followed the rules of good scientific practice.

Consent

Adriano Stephan Nascente, Tarcísio Cobucci, and Marco Araujo consented to participate in this research.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Adriano Stephan Nascente, Tarcísio Cobucci, and Marco Araujo contributed to the study conception and design. Adriano Stephan Nascente, Tarcísio Cobucci and Marco Araujo performed material preparation, data collection, and analysis. Adriano Stephan Nascente, Tarcísio Cobucci, and Marco Araujo read and approved the final manuscript.

References

[1] N. K. Fageria and A. S. Nascente, "A.S. Management of soil acidity of south american soils for sustainable crop production," *Advances in Agronomy*, vol. 128, pp. 221–275, 2014.

[2] H. D. M. Silva, O. E. Ferreira, G. H. G. Costa, and B. C. R. Guardiano, "Quantificação de bactérias solubilizadoras de fósforo em solo de reforma de canavial no bioma Cerrado com plantio de leguminosas/Quantification of phosphorus solubilizing bacteria in sugarcane reform soil in the Cerrado biome with legume planting," *Brazilian Journal of Development*, vol. 8, no. 2, pp. 11810–11820, 2022.

[3] C. Vermeiren, P. Kerckhof, D. Reheul, and E. Smolders, "Increasing soil organic carbon content can enhance the long-term availability of phosphorus in agricultural soils," *European Journal of Soil Science*, vol. 73, no. 1, 2022.

[4] A. S. Nascente, T. Cobucci, D. M. G. Sousa, and D. A. P. Lima, "Produtividade do feijoeiro comum afetada por fontes de fósforo com ou sem cálcio," *Revista de Ciências Agrarias-Amazon Journal of Agricultural and Environmental Sciences*, vol. 57, no. 2, pp. 180–185, 2014.

[5] A. S. Nascente and T. Cobucci, "Calcário na forma de micropartículas aplicado no sulco de semeadura aumenta produtividade do feijoeiro," *Revista Ceres*, vol. 62, no. 6, pp. 597–606, 2015.

[6] X. Zhang, E. A. Davidson, T. Zou et al., "Quantifying nutrient budgets for sustainable nutrient management," *Global Biogeochemical Cycles*, vol. 34, no. 3, pp. 1–25, 2020.

[7] M. Chen and T. E. Graedel, "A half-century of global phosphorus flows, stocks, production, consumption, recycling, and environmental impacts," *Global Environmental Change*, vol. 36, pp. 139–152, 2016.

[8] R. B. Chowdhury and X. Zhang, "Phosphorus use efficiency in agricultural systems: a comprehensive assessment through the review of national scale substance flow analyses," *Ecological Indicators*, vol. 121, Article ID 107172, 2021.

[9] G. T. M. Dias, "Marine bioclasts: calcareous algae," *Brazilian Journal of Genetics*, vol. 18, no. 3, pp. 307–318, 2000.

[10] V. M. M. Cavalcanti, *Plataforma Continental: A última fronteira da mineração brasileira*, National Department of Mineral Production, Brasília, Brazil, 2011.

[11] C. M. Soares, "Chemical study of the alga Lithothamniun calcareum and evaluation of the inhibitory activity of leukocyte rolling," *Master's Degree in Pharmaceutical Sciences-Faculty of Pharmacy, Federal University of Minas Gerais*, Belo Horizonte, Brasília, Brazil, 2009.

[12] T. V. Melo and A. M. A. Moura, "Utilização da farinha de algas calcáreas na alimentação animal," *Archivos de Zootecnia*, vol. 58, no. 224, pp. 99–107, 2008.

[13] P. C. Melo and A. E. Furtini Neto, "Avaliação do Lithothamnium como corretivo da acidez do solo e fonte de nutrientes para o feijoeiro," *Ciencia E Agrotecnologia*, vol. 27, no. 3, pp. 508–519, 2003.

[14] V. A. Bracchi, G. Piazza, and D. Basso, "A stable ultrastructural pattern despite variable cell size in *Lithothamnion corallioides*," *Biogeosciences*, vol. 18, no. 22, pp. 6061–6076, 2021.

[15] M. Lund, P. J. Davies, and J. C. Braga, "Coralline algal nodules off Fraser Island, eastern Australia," *Facies*, vol. 42, no. 1, pp. 25–34, 2000.

[16] G. M. Amado-Filho, G. W. Maneveldt, G. H. Pereira Filho et al., "Seaweed diversity associated with a Brazilian tropical rhodolith bed," *Ciencias Marinas*, vol. 36, no. 4, pp. 371–391, 2010.

[17] M. S. Foster, L. C. McConnico, L. L. Lundsten et al., "Diversity and natural history of a Lithothamnion muelleri Sargassum horridum community in the gulf of California," *Ciencias Marinas*, vol. 33, no. 4, pp. 367–384, 2007.

[18] P. C. Melo, *Evaluation of Lithothamnium as a Soil Acidity Corrector and Nutrient Source for Sweet Corn and Beans. 2002. 99f*, Federal University of Lavras, Lavras, Brazil, 2002.

[19] PrimaSea, "Primaz® harvesting the best results," 2023, http://www.primasea.com/produto/Primaz.

[20] H. S. Chaves, G. C. Galdino, T. S. Santiago, C. F. Oliveira Neto, D. C. Mariano, and R. S. Okumura, "Base saturation levels and soil acidity correctives in maize development," *Ciências Rurais em Foco*, vol. 7, pp. 35–39, 2022.

[21] Ministry of Agriculture and Livestock, "The national fertilizer plan," 2023, https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/plano-nacional-de-fertilizantes/o-plano-nacional-de-fertilizantes. Acessed.

[22] P. R. Ernani, M. S. Ribeiro, and C. Bayer, "Modificações químicas em solos ácidos ocasionadas pelo método de aplicação de corretivos da acidez e de gesso agrícola," *Scientia Agricola*, vol. 58, no. 4, pp. 825–831, 2001.

[23] Z. Dong, Y. Liu, B. Ci et al., "Estimation of nitrate nitrogen content in cotton petioles under drip irrigation based on wavelet neural network approach using spectral indices," *Plant Methods*, vol. 17, no. 1, 2021.

[24] A. S. Nascente, T. Cobucci, V. Brasil, and R. A. Reis Junior, "Cotton, bean, and soybean yield and nutrient redistribution in leaf sap in response to organic molecules complexed fertilizers," *January 2023*, vol. 17, pp. 74–82, 2023.

[25] G. S. Valladares, M. G. Pereira, and L. H. C. Anjos, "Adsorção de fósforo em solos de argila de atividade baixa," *Bragantia*, vol. 62, no. 1, pp. 111–118, 2003.

[26] A. Nolla, E. O. S. Alves, T. G. Silva, and A. V. Bordin, "Correção da acidez e disponibilização de fósforo e potássio em latossolo vermelho distrófico típico submetido à calagem incorporada e superficial/Correction of soil acidity and availability of phosphorus and potassium in an oxisol submited to surfaced and incorporated liming," *Brazilian Journal of Animal and Environmental Research*, vol. 3, no. 3, pp. 2478–2487, 2020.

[27] L. N. Miranda, J. A. Azevedo, J. C. C. Miranda, and A. C. Gomes, "Produtividade do feijoeiro em resposta a adubação fosfatada e a regimes de irrigação em solo de cerrado," *Pesquisa Agropecuária Brasileira*, vol. 35, no. 4, pp. 703–710, 2000.

[28] J. L. R. Torres, M. J. Santana, A. Pizolato Neto, and D. M. S. Vieira, "Productivity of bean on sheets of irrigation and soil covers," *Bioscience Journal*, vol. 29, no. 4, pp. 833–841, 2013.

[29] E. Rotilli, R. Fidelis, M. Santos, H. Barros, and L. Pinto, "Eficiência do uso e resposta à aplicação de fósforo de cultivares de arroz em solos de terras altas," *Bragantia*, vol. 69, no. 3, pp. 705–710, 2010.

[30] R. B. Chowdhury, G. A. Moore, A. J. Weatherley, and M. Arora, "A review of recent substance flow analyses of phosphorus to identify priority management areas at different geographical scales," *Resources, Conservation and Recycling*, vol. 83, pp. 213–228, 2014.

[31] R. B. Chowdhury, G. A. Moore, A. J. Weatherley, and M. Arora, "A novel substance flow analysis model for analysing multi-year phosphorus flow at the regional scale," *Science of the Total Environment*, vol. 572, pp. 1269–1280, 2016.