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Article

Agronomic and Physicochemical Quality of Broccoli Cultivated Under Different Fertilizers and Phosphorus Rates

Dinamar Márcia da Silva Vieira [1], Reginaldo de Camargo [1], Miguel Henrique Rosa Franco [2], Valdeci Orioli Júnior [3], Cintia Cristina de Oliveira [3], Arcângelo Loss [4], Fausto Antônio Domingos Júnior [3], Maytê Maria Abreu Pires de Melo Silva [3] and José Luiz Rodrigues Torres [3,*]

[1] Department of Agronomy, Agricultural Sciences Institute, Federal University of Uberlandia, Glória Campus, Uberlandia 38410-337, MG, Brazil; marcinha_0202@hotmail.com (D.M.d.S.V.); rcamargo@ufu.br (R.d.C.)
[2] AGROCP Company, Uberlândia 38408-684, MG, Brazil; miguelmhrt@yahoo.com.br
[3] Federal Institute of Triangulo Mineiro, Uberaba Campus, 4000 São João Batista Ribeiro St., Uberaba 38064-790, MG, Brazil; valdeci@iftm.edu.br (V.O.J.); cintia@iftm.edu.br (C.C.d.O.); fausto@iftm.edu.br (F.A.D.J.); mayte@iftm.edu.br (M.M.A.P.d.M.S.)
[4] Agricultural Sciences Center, Department of Rural Engineering, Federal University of Santa Catarina, Campus Florianópolis, Florianópolis 88035-972, SC, Brazil; arcangelo.loss@ufsc.br
* Correspondence: jlrtorres@iftm.edu.br

Abstract

The aim of this study was to evaluate the agronomic performance and physicochemical characteristics of broccoli grown under different doses and sources of special phosphorus (P) fertilizers and their residual effect on the soil, in Cerrado mineiro. A randomized block design arranged in a split-plot scheme was employed, where three P sources—T1 = Conventional monoammonium phosphate (CMP); T2 = Polymerized monoammonium phosphate (PCMP); T3 = Granulated organomineral fertilizer (GOF)—along with four P_2O_5 rates—1–0 (No P); 2–50% (200 kg ha^{-1} P_2O_5); 3–75% (300 kg ha^{-1} P_2O_5); and 4–100% (400 kg ha^{-1} P_2O_5)—were assessed. Evaluations included the number of leaves (NL), head fresh (HFM) and dry mass (HDM), yield (YLD), soil fertility at harvest, plant nutritional status, and the physicochemical quality of the harvested broccoli. It was observed that GOF provided the best agronomic performance (HFM, HDM and YLD) of the broccoli and the greatest residual effect in the soil compared to PCMP and CMP. The moisture, ash, protein, lipid, total titratable acid and ascorbic acid contents were not significantly ($p < 0.05$) affected by the fertilizers used, on the other hand, total soluble solids and hydrogen potential showed the highest and lowest values, respectively, with CMP. The best agronomic performance, the highest phosphorus content in the soil and plant and the best physical–chemical quality of the broccoli occurred at a dose of 100% (400 kg ha^{-1} of P_2O_5) of the recommendation for the crop in all three fertilizers evaluated.

Keywords: special fertilization; polymerized fertilizer; organomineral; production

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1. Introduction

Broccoli (*Brassica oleracea* var. italica) has a high nutritional and commercial value and can be grown in any region of Brazil, having become one of the most consumed vegetables in the country [1–3]. Global broccoli production has reached over 19 million megagrams per year, with China, India, and the United States being the largest producers, in a planted area exceeding 1.0 million hectares [4,5].

Brazil stands out as the largest producer of broccoli in South America, with an estimated cultivated area of 15,000 hectares, accounting for approximately 48% of the region's total, and more than 290,000 megagrams per year. Consumption of this vegetable has grown exponentially in recent decades, with a 63% increase in the area cultivated in the country in the last 10 years. However, the largest producers are still concentrated in the Southeast region of the country, with the state of São Paulo leading production (30,045 megagrams), closely followed by Minas Gerais (27,659 megagrams) [6,7].

Broccoli cultivated in Brazil is produced using cultivars with high genetic potential, which are part of a technological package that is highly dependent on industrialized inputs, as these plants have a high capacity for extracting nutrients from the soil, requiring the use of large amounts of fertilizers for their cultivation [8]. Furthermore, it remains a conventionally grown crop, involving two harrowing operations after each cycle and highly soluble mineral fertilizers, which increases the potential for erosion and nutrient leaching [9,10]).

When broccoli is cultivated in the Brazilian Cerrado, where acidic soils with low natural fertility predominate and the mineralogy is rich in iron (Fe) and aluminum (Al) oxides, with a predominance of kaolinite, phosphate adsorption tends to be high due to the presence of positive charges on the surface of these clay minerals. As a result, a considerable part of the inorganic P added to the soil via fertilizers is retained with so much energy that its balance with the P in the solution disappears, and it is no longer useful for the plant's immediate growth. In this scenario, leaching and adsorption losses tend to be higher, maximizing the need for proper management [11–16]. Filgueira [17] and Oliveira et al. [18] emphasize that brassicas can extract, on average, about 180 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5, and 150 kg ha^{-1} of K_2O during the entire cultivation cycle.

Among the technological innovations being used to reduce nutrient leaching and phosphorus (P) adsorption in the Cerrado and other regions of the country, granular organomineral fertilizer (GOFs) and polymer-coated phosphate fertilizers (PCMPs) have stood out, as these products are formulated to release nutrients in a controlled and gradual manner throughout the crop cycle [19,20].

GOFs are created through the physical mixing or combination of mineral and organic fertilizers of various origins, as the organic matter present in the granule increases the soil cation exchange capacity, reducing nutrient losses through leaching and adsorption [21,22]. On the other hand, PCMPs, coated with polymers, provide a slower initial release of nutrients through different mechanisms. The nutrient coating reduces its contact with Fe and Al oxides and clay minerals, preventing the formation of stable compounds and decreasing P adsorption in the soil. Consequently, this allows the nutrient to remain available in the soil for longer and optimizes its plant absorption, reducing losses, as well as having a considerable residual effect on the soil [20,23,24].

Some studies using GOFs and PCMPs as a source of P have already been conducted with broccoli and other crops, which have shown them to be more appropriate fertilizers for use in tropical soils, as they are formulated to release nutrients in a controlled and slower manner, resulting in better utilization by plants and reduced losses due to adsorption [13,19–21,25].

According to Altiere and Nicholls [26], agricultural practices and the intensive use of inorganic fertilizers can cause nutritional imbalances in plants and alter the physicochemical quality of the product. In their study, Storck et al. [27] analyzed the physicochemical composition of the edible part of cauliflower and broccoli and observed the following values for carbohydrates, crude fiber, protein, lipids, ash, and moisture, respectively: 4.5, 2.4, 1.9, 0.2, 0.6, and 92.8% for cauliflower and 4.0, 2.9, 3.6, 0.3, 0.8, and 91.2% for broccoli. In cabbage, Ferreira et al. [28] reported values of 1.03% for total titratable acidity, 2.77% for carbohydrates, and 5.56°Brix for total soluble solids. According to Ornellas [29], broccoli and cauliflower are morphologically similar plants, with a nutritional value that varies depending on the plant part, averaging from 1% to 3% protein, 4% to 24% carbohydrates, and lipids present in small amounts.

Several studies have already evaluated the agronomic performance of broccoli grown conventionally using highly soluble mineral fertilizers [8,9,18,30]. However, studies evaluating the use of special fertilizers in combination with the physicochemical composition of broccoli are nonexistent, making this study unique.

In this context, the hypothesis tested in this study is that special fertilizers (GOFs and PCMPs) are more efficient in providing P in the weathered soils of the Cerrado and can alter the nutritional composition of broccoli. The aim of this study was to evaluate the agronomic performance and physicochemical characteristics of broccoli grown under different doses and sources of special phosphorus fertilizers and their residual effect on the soil, in Uberaba, Minas Gerais, Brazil.

2. Materials and Methods

2.1. Characterization of the Area

The study was conducted in an experimental area in Uberaba, Minas Gerais, Brazil, located at 19°39′19″ S and 47°57′27″ W, at approximately 800 m, from March to June 2024.

In this same area, the previous year (2023), two consecutive cycles of broccoli were grown, after which the area was left fallow for three months, where the spontaneous vegetation developed naturally, and then the area was prepared again for another cycle of cultivation. The soil preparation in the area consisted of two harrowings, one deep harrowing with an 18-disk harrow (76.2 cm in diameter), followed by a shallow harrowing with a light harrow equipped with 44 disks (60.96 cm in diameter).

The soil in the experimental area was classified as Oxisol [31], with a sandy loam texture and the following particle-size distribution at the 0–20 cm layer—260, 700, and 40 g kg^{-1} of clay, sand and silt, respectively—as well as the following chemical attributes (Table 1).

Table 1. Chemical attributes of the 10–20 cm soil layer in the experimental area at the beginning of broccoli planting in Uberaba, Minas Gerais, Brazil.

Layer	pH		Ca	Mg	Al	H + Al	P	K	S	SOC
cm	H_2O	SMP	cmol$_c$ dm^{-3}				mg dm^{-3}			g dm^{-3}
0–20	6.00	5.40	1.80	0.45	0.00	2.20	0.71	0.22	8.71	20.20
			B	Cu	Fe	Mn mg dm^{-3}	Zn			
			0.20	1.61	24.71	13.20	0.71			

pH of H_2O determined in a soil to water ratio of 1:1; SOC = soil organic carbon; H + Al determined based on the Shoemaker, Mac Lean, and Pratt (SMP) index, which is a method for analyzing and correcting soil acidity, based on the buffering power of the soil.

The climate is classified as Aw-type, a tropical savanna with a hot climate according to the updated Koppen classification [32], characterized by hot, rainy summers and cool, dry winters. The region has an accumulated annual rainfall of 1600 mm, an average annual temperature of 22.6 °C and relative humidity of 68% [33]. During the experiment, cumulative precipitation totaled 456 mm, and the average temperature was 21 °C from March to June 2024 (Figure 1).

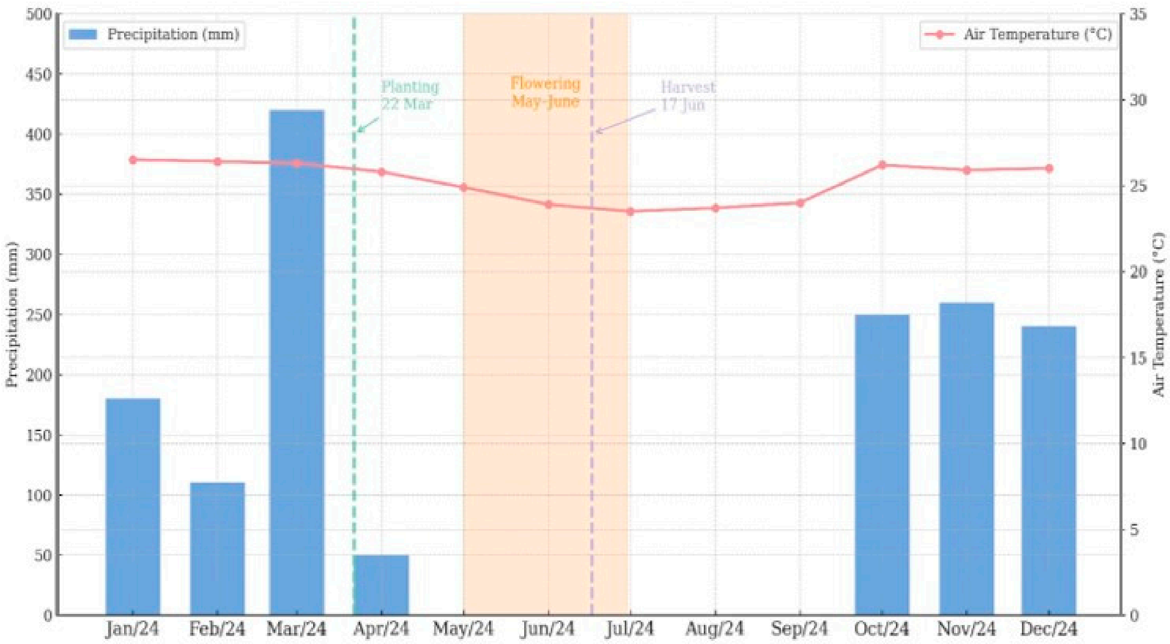

Figure 1. Monthly rainfall and average temperature recorded at the weather station of the Federal Institute of Education, Science and Technology of Triângulo Mineiro (IFTM), Uberaba Campus, Minas Gerais, from January to December 2024.

2.2. Experimental Design and Treatments

The experiment was conducted in a randomized block design, arranged in a split-plot scheme with four replications. In the main plots, three P sources were evaluated: (1) conventional monoammonium phosphate (CMP) (formula 11-52-00); (2) polymer-coated monoammonium phosphate (PCMP) (formula 11-52-00); and (3) granular organomineral fertilizer (GOF) (formula 05-26-00). In the subplots, four phosphorus application rates were tested: 0 (no P applied), 50% (200 kg ha^{-1} of P_2O_5), 75% (300 kg ha^{-1} of P_2O_5), and 100% (400 kg ha^{-1} of P_2O_5) of the recommended rate for broccoli [34].

During its growth cycle, broccoli extracts a significant amount of P from the soil, which can vary from 30 to 60 kg of P_2O_5 [17]. However, in Oxisol, the availability of P in the soil is minimal and there is still high adsorption of this element. In this scenario, Ribeiro et al. [34] recommend doses of phosphate fertilizers ranging from 250 to 400 kg ha^{-1} of P_2O_5 to meet the crop's demand.

The distribution of these plots (main treatment) and subplots (secondary treatment) in the field were all randomly selected, and all sampling was carried out in each subplot, always with four replicates.

The GOF used, based on filter cake, was formula 05-26-00 (N–P–K), which contained 8% total organic carbon (0.14 g dm^{-3} of organic matter).

2.3. Additional Information

Single-head broccoli seedlings were grown in 128-cell polystyrene trays filled with Bioplant commercial substrate, using the seed of the hybrid broccoli cultivar Avenger from the Sakata company, which has an average cycle of 100 days, an average mass of 700 g per head and an average yield of 20 Mg ha^{-1} [19,32].

The seedlings were produced in 128-cell trays in a greenhouse covered with plastic and enclosed sidewalls, irrigated by micro-sprinklers, at a commercial nursery specializing in brassica seedlings in Uberaba, Minas Gerais, Brazil.

After transplanting the seedlings, weed management was carried out through the application of fluazifop-p-butyl (Fusilade® 250 EW, 175 g ha^{-1} of a.i.) (São Paulo, SP, Brazil), supplemented, when necessary, by manual hoeing or mowing using a motorized handheld brush cutter to keep the area free of weeds.

The broccoli seedlings were transplanted to the field on 22 March 2024, into holes previously prepared with the help of hand diggers, with an approximate diameter of 0.15 m and a depth of 0.18 m, at a spacing of 0.80 × 0.50 m, to achieve a final stand of 25,000 plants per hectare.

The harvesting began on 17 June 2024, when the plants reached the point of commercial maturity, when the crowns are large, green and firm, with tightly closed edges.

No raised beds were built in the area, and the experimental plots consisted of four rows, each four meters long, with six plants per row, totaling twenty-four plants per plot, and the eight central plants were considered useful for evaluations of fresh head weight (FHW), dry head weight (DHW) and crop yield (YLD). Tracks 1.0 m wide were left throughout the area to separate the blocks and make harvesting easier.

All the planting and top-dressing fertilizer was applied directly to the holes on 20 March 2024, where the seedlings were later transplanted. The fertilizer doses were determined based on the chemical analysis of the soil and according to the recommendations of the Minas Gerais State Soil Fertility Commission [34], with 150 kg ha^{-1} of N, 400 kg ha^{-1} of P_2O_5 and 100 kg ha^{-1} of K_2O being applied for an expected yield of 20 Mg ha^{-1}. The entire dose of P was applied at planting, while N and K were divided four times, with 20% applied at planting and the rest applied at 20 (20%), 40 (30%), and 60 (30%) days after transplanting.

At the same time as the fertilizer splits, three foliar sprays were applied to provide boron (B), molybdenum (Mo), and cobalt (Co) at 20, 40, and 60 days after transplanting the seedlings. The solution contained 1 g L^{-1} of boric acid (17% B) and 2.7 mL of Vitaphol CoMo®, a product containing 10% Mo and 2% Co. Applications were carried out to completely cover the leaves without runoff of the boric acid solution at a concentration of 1 g L^{-1}, plus 0.5 g L^{-1} of ammonium molybdate [35].

The plants were irrigated daily using a fixed conventional sprinkler system equipped with sectorial sprinklers with a 560 L h^{-1} flow rate, spaced 9 m apart. Irrigation was applied for approximately 20 to 30 min daily to maintain soil moisture near field capacity.

2.4. Evaluations

The broccoli was harvested when the inflorescences were fully developed with flower buds still attached and compact, firm heads. Harvesting lasted 30 days, during which evaluations were carried out every three days, starting 80 days after transplanting.

In the harvested material, the number of leaves (NL) and fresh head weight (FHW) were determined on an analytical scale and crop yield (YLD) was determined by quantifying the number of heads produced in the area. Part of the harvested material was taken to the laboratory, chopped into smaller pieces to facilitate drying, and placed in a forced-air circulation oven at 65 °C for 72 h or until reaching constant weight to determine dry head weight (DHW). The FHW and DHW results were expressed in kilograms per plant (kg plant^{-1}) and productivity of broccoli heads in megagrams per hectare (Mg ha^{-1}).

Samples of recently matured leaves were collected at the broccoli head formation stage to analyze the nutritional status of the plants [36]. Total nitrogen was analyzed using the Kjeldahl distillation method, P by colorimetry, and K by flame atomic emission spectrophotometry. Ca and Mg were determined by atomic absorption spectrophotometry, and S by turbidimetry [37]. The total content of each nutrient was estimated by multiplying the percentage of the nutrient in each sample by the total dry weight.

After the broccoli harvest, a Dutch auger collected individual soil samples from the eight planting holes where the usable area plants had been harvested. These samples were combined to form a composite sample per plot, with four replications, collected at a depth of 15 cm to quantify the residual effect of the fertilizers used after each cycle.

After soil sampling, the samples were air-dried, crushed, and passed through a 2.0 mm mesh sieve, thus obtaining the air-dried fine earth fraction (ADFE), which was used for fertility analyses, following the analytical methods described by Teixeira et al. [35].

Soil pH in water was determined using a 1:2.5 soil-to-solution ratio. The soil was left in contact with distilled water for one hour, after which the pH was measured using a benchtop pH meter. Exchangeable Ca^{2+}, Mg^{2+}, and Al^{3+} and potential acidity (H^+ + Al) were extracted using 1 mol L^{-1} KCl solution and quantified by titration. P and K were extracted using a double-acid solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4) following the Mehlich-1 method and analyzed by colorimetry (P) and flame photometry (K^+), respectively [37].

A portion of the harvested plants was taken to the Food Analysis Laboratory of IFTM, where chemical analyses were conducted using the following methods: moisture by the gravimetric method; protein by the Kjeldahl method, through the determination of the nitrogen content in the food; lipids by the Soxhlet method (gravimetric), based on the amount of material solubilized by the solvent; ascorbic acid by the Tillmans method [38]. The fixed mineral residue (ash) was determined by calcining the sample in a muffle furnace at 550 °C until light-colored ash was obtained. The pH was measured with a pH meter with the sample at 25 °C. Total soluble solids were measured by electronic refractometry, carbohydrates were calculated as the difference between the values of each food component, and the total caloric value was calculated based on the caloric content of each food constituent [39].

Crude fiber was determined using the gravimetric method after acid digestion, while total titratable acidity and the acidity due to the predominant organic acid were determined according to the methodology described by IAL [40].

The analyses of protein, crude fiber, and lipids were performed on dry samples, and the indices for fresh mass were calculated later. The remaining analyses were conducted on fresh samples 24 h after harvest, which were kept refrigerated and stored in five layers of nylon bags during the entire period, according to AOAC methodology [39].

2.5. Statistical Analysis

The residual normality assumptions, variance homogeneity, and block additivity were tested using the Shapiro–Wilk and Bartlett tests, respectively. The values of the evaluated variables were subjected to analysis of variance using the F-test. When significant, quantitative factors (fertilizer rates) were further analyzed by regression using SigmaPlot software, version 2012. The means of qualitative factors (soil treatments) were grouped using the Scott–Knott test ($p < 0.05$; 0.01) with the aid of the Agroestat software, version 2024, developed by [41].

The figures were produced using the Python version 3.12 and the Matplotlib package version 3.8.2 [42], using linear or polynomial regressions adjusted by the least squares method.

3. Results and Discussion

3.1. Agronomic Attributes

When analyzing the agronomic attributes, in general, no significant differences ($p < 0.05$) were observed in the NL among the fertilizers used. However, this was not the case for the other parameters, as the values for HFM (0.91 kg), HDM (0.29 kg), and YLD (22.82 Mg ha^{-1}) were higher ($p < 0.05$) with the organomineral fertilizers (GOFs), followed by polymer-coated phosphate fertilizers (PCMPs) (0.86 kg; 0.26 kg and 21.43 Mg ha^{-1}), using conventional monoammonium phosphate (CMP) (0.69 kg; 0.22 kg and 20.62 Mg ha^{-1}), respectively (Table 2).

Table 2. Agronomic traits of broccoli plants during the third cultivation cycle as affected by different fertilizer types and phosphorus application rates in Uberaba, MG, 2024.

Treatments	Agronomic Attributes			
	NL	**HFM**	**HDM**	**YLD**
	-	**kg plant^{-1}**		**Mg ha^{-1}**
	Fertilizer (F)			
CMP	25.81	0.69 c	0.22 c	20.62 c
PCMP	26.19	0.86 b	0.26 b	21.43 b
GOF	25.37	0.91 a	0.29 a	22.82 a
%	Rate (R)			
0	23.50 b	0.46 c	0.21 c	19.26 b
50	25.34 a	0.80 b	0.24 b	20.59 a
75	26.33 a	0.97 a	0.27 a	21.04 a
100	27.00 a	0.98 a	0.28 a	21.85 a
F-test for F	0.80 ^{ns}	12.58 **	8.02 *	8.46 *
F-test for R	7.05 **	359.05 **	189.98 **	3.02 *
F-test for F × R	0.79 ^{ns}	18.76 **	4.47 **	17.86 **
CV% F	5.91	9.22	10.15	7.11
CV% R	6.97	4.76	10.39	4.80

Means followed by the same lowercase letters in the column do not differ according to the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$). ^{ns} = Not significant; CV = Coefficient of variation; CMP = Conventional monoammonium phosphate; PCMP = Polymerized monoammonium phosphate; GOF = Granulated organomineral fertilizer; NL = Number of leaves; HFM = Head fresh mass; HDM = Head dry mass; YLD = Yield.

The higher production observed with the application of the GOF can be explained by the presence of organic matter combined with minerals in the same granule, which protects the P and releases the nutrient more slowly, compared to PCMP and CMP, reducing the issue of P adsorption and providing a greater amount of P available for plant absorption throughout its entire growth cycle.

The GOF result from the physical mixing or combination of mineral and organic fertilizers of various origins, as the organic matter present in the granule contributes to increasing the soil cation exchange capacity [22]. It also promotes the proliferation of beneficial soil microorganisms, which solubilize mineral fertilizers, providing a greater residual effect of the applied phosphate fertilization through competition between the organic acids released and phosphate ions for adsorption sites in the soil [8,13,21].

According to Figueiredo et al. [43] and Cardoso et al. [44], the gradual release of nutrients promoted by the polymer coating of PCMP reduces its contact with Fe and Al oxides and clay minerals; thus, there is no formation of stable compounds, which would reduce the adsorption of P in the soil. This explains why PCMP treatment yields better results than CMP. Among the fertilizers used, CMP has the highest solubility and availability of P in the soil, as this nutrient is not protected by polymers or organic matter.

The P is one of the macronutrients least required by plants; however, it has the most frequently limited agricultural production in the Brazilian Cerrado [45]. This is due to the predominance of Oxisols in the region—highly weathered and acidic soils—where most of the applied phosphate fertilizer tends to precipitate as aluminum- and iron-bound phosphorus (P-Al and P-Fe). In more alkaline soils, the predominant precipitation occurs in P-Ca [46].

The low natural availability of P in tropical soils, as occurs in the Brazilian Cerrado, leads to the application of this macronutrient in production systems, mainly via soluble inorganic fertilizers in larger quantities, which in a way are necessary for the system as an alternative to circumvent the problem of strong nutrient adsorption [47].

The initial chemical analysis of this soil showed a P content of 21.7 mg dm^{-3}, higher than the critical level for crop production, established by Alvarez et al. [48] at 15.1 mg dm^{-3} of P. This likely explains the 19.26 Mg ha^{-1} yield at the zero P rate (No P), which was only 12% lower than the highest yield obtained (21.85 Mg ha^{-1}).

Regarding application rates, similar values of NL, HFM, HDM, and YLD were observed at the 100% (400 kg ha^{-1} P_2O_5) and 75% (300 kg ha^{-1} P_2O_5) rates. These values were higher than those recorded at the 50% rate and in the control treatment (no P). However, this difference was significant only for HFM and HDM when using the phosphate fertilizer recommended for the crop. These results confirm the importance of using these phosphate fertilizer sources, which mitigate the problem of adsorption that occurs in these Cerrado soils, as the values obtained for HFM, HDM, and YLD were significantly higher with GOF and PCMP fertilizers, whose main characteristic is the protection of P by organic matter and by the polymer used, as well as the slow release of nutrients.

Some studies show that for growing broccoli in poor soils with adsorption problems, the recommended doses of phosphate fertilizers range from 250 to 400 kg ha^{-1} of P_2O_5 in the form of superphosphates, in areas with a pH ranging from 6.0 to 6.8 [7,17,34], a condition that justifies the best yields observed at the 100% dose (400 kg ha^{-1} of P_2O_5) applied to the three fertilizers evaluated.

The Oxisol that predominates in the study area has a low clay content (260 g kg^{-1}) but high levels of Fe and Al, making it a soil with a high capacity for P adsorption, thus reducing its availability to plants, as observed by Loss et al. [49]. Torres et al. [14] and Silva et al. [16] highlight that additions of P to the soil beyond the amounts absorbed by plants increase the fractions of inorganic P, leading to a saturation process of adsorption sites.

According to Cardoso et al. [15] and Vieira et al. [50,51], fertilizer efficiency does not depend solely on the doses of fertilizer being applied, as the availability of phosphorus from the application of soluble phosphates depends on the reaction that controls the amount of the nutrient in the soil solution, mainly chemical adsorption or precipitation, the pH around the fertilizer granule, and the type of precipitate that predominates.

However, it is known that acidity limits plant development in tropical soils. Nevertheless, adding organic matter to the system reduces the negative effects caused by acidity, as well as reducing the effects of aluminum toxicity in experimental or field conditions, promoting better crop performance, even in adverse conditions [25].

Based on the analysis of significant interaction breakdowns using regression curves (Table 2), it was observed that for the CMP, PCMP, and GOF, a linear regression model best fit the data for HFM (Figure 2A), HDM (Figure 2B), and YLD (Figure 2C). Increasing fertilizer rates resulted in corresponding increases in these parameters, reaching maximum values of 0.98 kg, 0.28 kg, and 21.85 Mg ha^{-1}, respectively, at the 100% recommended fertilization rate for the crop.

The beneficial effect of P is directly linked to the plant's ability to accumulate biomass during its initial growth phase, thereby increasing the leaf area exposed to light, as demonstrated by Oliveira et al. [18], who correlated increasing P rates with an increase in the leaf area index, resulting in greater photosynthetic capacity.

This linear increase in production with increasing fertilizer rates is consistent with studies conducted by Fageria [52], Aguilar et al. [19,24], and Sousa et al. [53], who identified a direct relationship between increasing P rates and HDM accumulation in vegetables. These authors highlighted that P is essential in biomass production, especially in intensive cultivation systems. These results reflect the efficiency of phosphate fertilization in broccoli cultivation and align with Malavolta [54], who emphasizes that P optimizes nutrient uptake and plant development when applied at adequate rates.

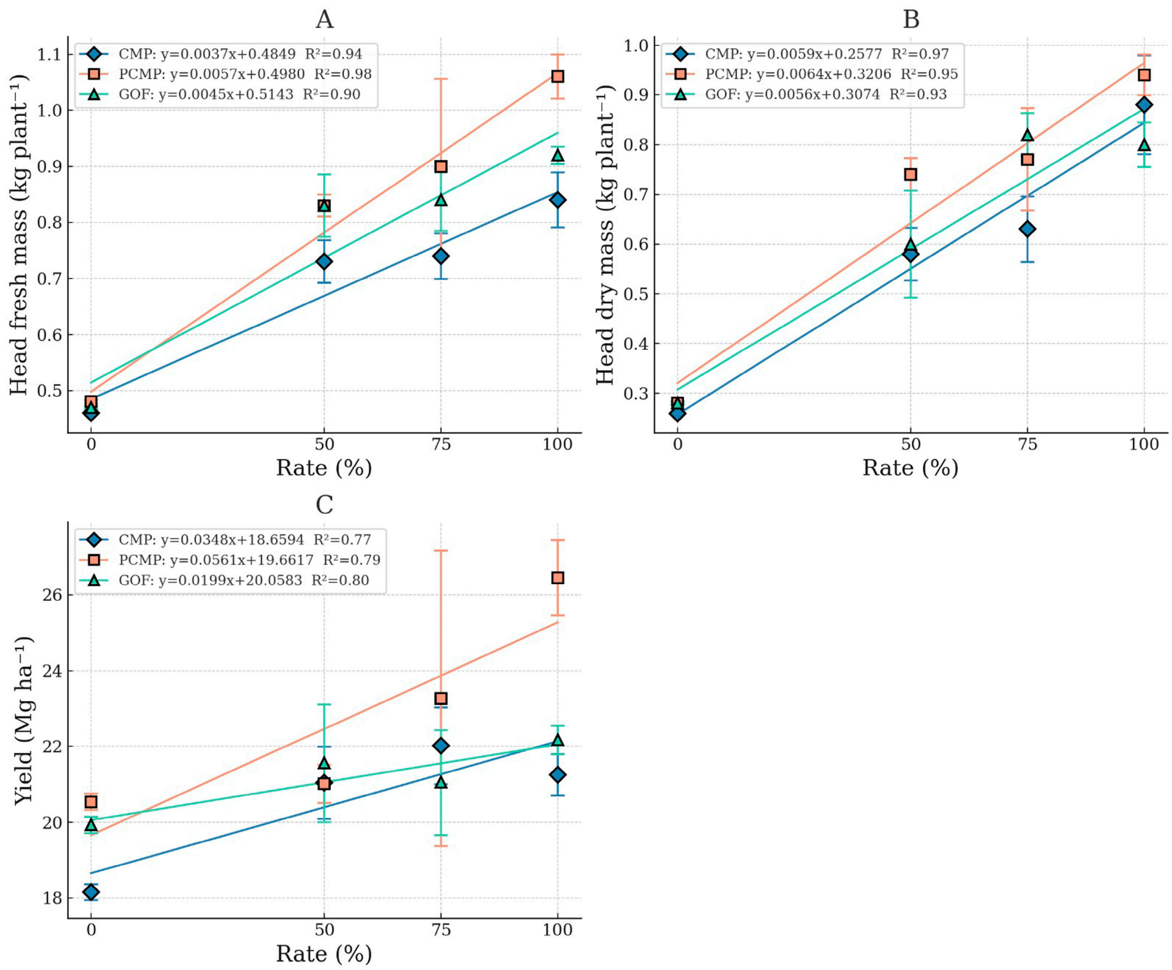

Figure 2. Linear regression analysis of the interaction effects on head fresh mass (HFM) (**A**), head dry mass (HDM) (**B**), and yield (YLD) (**C**) of broccoli grown in Uberaba, MG, 2024.

The chemical analysis of the soil immediately after harvest showed that the soil in the three areas had similar pH values, ranging from 5.62 to 5.65 among the fertilizers used, with the highest values recorded at the 100% rate (5.70). For P (105.99 mg dm^{-3}) and K (116.68 mg dm^{-3}) contents, the values were significantly higher where the GOF was applied, compared to those observed with PCMP (94.16 and 96.85 mg dm^{-3}) and CMP (75.92 and 100.47 mg dm^{-3}). For Ca, Mg, and H + Al, the nutrient contents in the soil were similar for PCMP and GOF, but for CMP, Ca and Mg were lower than the others. Regarding the rates, the highest nutrient contents in the soil always occurred where the 50% and 100% rates were applied for all three fertilizers (CMP, PCMP, and GOF) (Table 3).

The initial P content in the soil was 21.7 mg dm^{-3}, which, when compared with the levels observed after fertilization with CMP (87.71 mg dm^{-3}), PCMP (88.81 mg dm^{-3}) and GOF (101.09 mg dm^{-3}), showed increases in the P content in the soil of 404%, 409% and 466%, respectively. In other words, the application of different fertilizers provided greater availability of nutrients for plant absorption, especially GOF. In addition, the decomposition and nutrient cycling of organic matter contributed to improving soil fertility in the area.

According to Figueiredo et al. [43], P may be unavailable in the soil in areas with high pH, altering the efficiency of polymer-coated phosphate fertilizers (PCMPs) and controlled-release fertilizers (GOFs). However, this behavior was not observed in this study, as the areas had a pH (in H_2O) ranging from 5.62 to 5.65. Even so, the GOF area had the highest values for all nutrients evaluated, which is probably related to the organic matter present in the fertilizer formulation, which slowly releases these nutrients into the soil solution (Table 3).

Table 3. Chemical analysis of the soil immediately after broccoli harvest under different fertilizers and phosphorus (P) rates in Uberaba, MG, 2024.

Treatment	Chemical Attributes					
	pH	**P**	**K**	**Ca**	**Mg**	**H + Al**
	H_2O	**mg dm^{-3}**		**$cmol_c$ dm^{-3}**		
	Fertilizer (F)					
CMP	5.63	87.71 b	150.91 b	1.34 b	0.39 b	4.38
PCMP	5.65	88.81 b	135.35 c	1.53 a	0.45 a	4.28
GOF	5.62	101.09 a	167.50 a	1.55 a	0.47 a	4.38
	Rate (R)					
0	5.05 b	50.51 d	142.17 b	1.39 b	0.38 b	4.05 b
50	5.61 b	95.78 c	146.91 b	1.45 b	0.44 a	4.40 a
75	5.62 b	108.39 b	155.76 a	1.52 a	0.45 a	4.45 a
100	5.70 a	115.47 a	162.84 a	1.53 a	0.46 a	4.47 a
F-test for F	0.43 ^{ns}	0.27 **	0.36 **	1.20 **	0.88 **	1.00 ^{ns}
F-test for R	1.09 **	8.96 *	16.31 **	22.10 **	9.76 *	0.79 **
F-test for F x R	0.84 ^{ns}	5.58 **	13.45 **	10.45 **	4.13 **	0.56 ^{ns}
CV% F	1.12	10.74	9.84	6.66	12.10	6.10
CV% R	2.04	8.58	7.61	8.80	14.22	9.71

Means followed by the same lowercase letters in the column do not differ according to the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$). ^{ns} = Not significant; CV = Coefficient of variation; CMP = Conventional monoammonium phosphate; PCMP = Polymerized monoammonium phosphate; GOF = Granulated organomineral fertilizer.

Regression analysis of the significant interactions revealed a linear trend for P and K (Figure 3A), as well as for Ca and Mg (Figure 3B), indicating that soil nutrient contents increased with higher fertilizer application rates. This behavior is more pronounced for P, likely because a portion of the applied P is adsorbed by the soil, meaning that at higher rates, more P remains available in the soil for subsequent plant uptake.

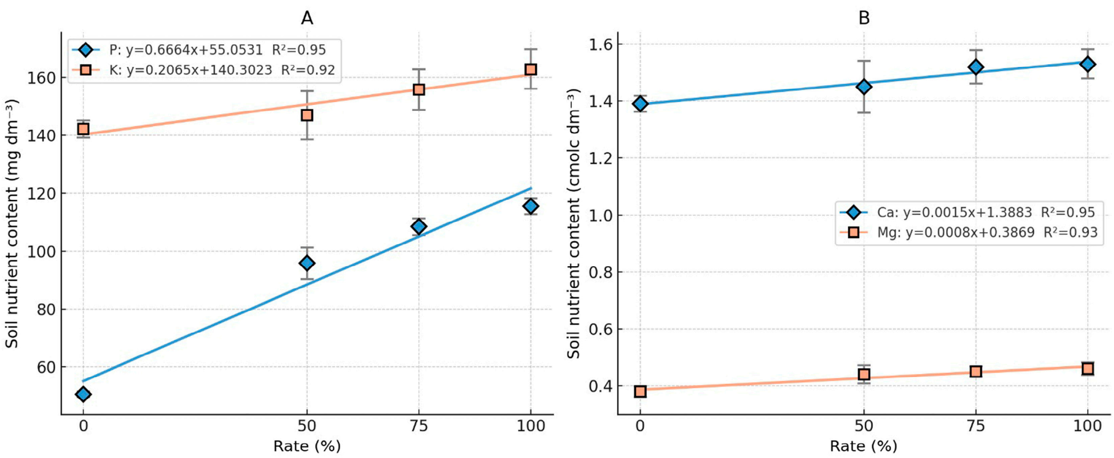

Figure 3. Linear regression analysis of the interaction effects on soil P and K (**A**), and Ca and Mg (**B**) in the broccoli cultivation area in Uberaba, Minas Gerais, Brazil, in 2024.

The combination of nutrients from organic and mineral sources in GOF proved promising in minimizing the issues of adsorption that occur in the weathered soils of the Cerrado, as increases in soil P were observed in both quantities and a linear trend over the evaluation period due to the proposed mixtures compared to the control and the application of isolated sources [20], results similar to those observed in this study.

The composition of GOF includes fulvic and humic components in the organic fractions, which stimulate microbial flora around the root system, facilitating nutrient retention and release, water retention, aeration, aggregation, as well as providing residual nutrient effects in the soil [13,49,53]. In addition, the authors highlight that these components optimize the absorption of nutrients contained in fertilizers, reducing P adsorption in the soil, as organic biomass acts to block phosphate adsorption sites, protecting P from direct contact with soil colloids.

Foliar analysis showed no significant differences among the fertilizers evaluated for N, P, and K; however, the availability of these nutrients in the plant increased as the fertilizer rates increased, reaching the highest value at the 100% rate (Table 4).

Table 4. Foliar nutrient contents in broccoli immediately after the cycle, under different fertilizer types and phosphorus application rates, in Uberaba, MG, 2024.

Treatment	**Nutritional Composition**		
	N	**P**	**K**
		g kg^{-1}	
		Fertilizer (F)	
CMP	44.92	5.11	33.17
PCMP	46.39	5.08	31.87
GOF	49.19	5.63	33.28
		Rate (R)	
0	41.76 b	4.93 b	29.65 b
50	41.94 b	5.31 a	32.49 a
75	43.39 b	5.35 a	33.67 a
100	60.24 a	5.52 a	35.28 a
F-test for F	0.92 ^{ns}	0.10 ^{ns}	1.43 ^{ns}
F-test for R	6.63 **	2.72 **	2.70 *
F-test for F x R	1.92 ^{ns}	3.98 *	1.62 *
CV% F	6.23	4.47	5.05
CV% R	9.76	13.59	8.72

Means followed by the same lowercase letters in the column do not differ according to the Scott–Knott test (** = $p < 0.05$; * = $p < 0.01$). ^{ns} = Not significant; CV CV = Coefficient of variation; CMP = Conventional monoammonium phosphate; PCMP = Polymerized monoammonium phosphate; GOF = Granulated organomineral fertilizer.

Nitrogen, the most absorbed nutrient by plants, is also the most abundant in plant tissues and tends to be released slowly when this organic matter undergoes decomposition/mineralization. Since GOF contains organic matter and nutrients in the same granule, this nutrient is gradually released and made available to plants [49].

Foliar analysis of broccoli at harvest revealed N contents ranging from 44.92 to 49.19 g kg^{-1}, P from 5.08 to 5.63 g kg^{-1}, and K from 31.87 to 33.28 g kg^{-1} (Table 4). All values fell within the sufficiency range for the crop—30 to 55 g kg^{-1} for N, 3 to 8 g kg^{-1} for P, and 25 to 50 g kg^{-1} for K—considered adequate for plant development, according to Trani and Raij [35], indicating that the plants were well nourished at the time of sampling.

The regression analysis of the significant interactions revealed a linear trend for P (Figure 4A) and K (Figure 4B), indicating that the foliar contents of these nutrients increased with higher soil application rates. This behavior was expected, as P and K are among the nutrients most readily absorbed by plants when available in the soil.

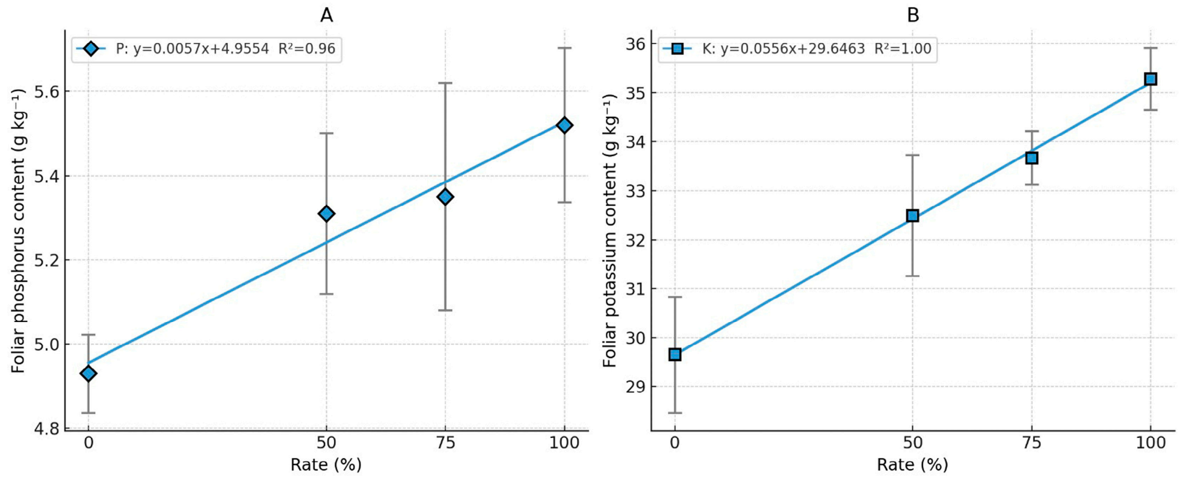

Figure 4. Linear regression analysis of the interaction effects on foliar P (**A**) and K (**B**) contents in broccoli grown in Uberaba, MG, 2024.

According to [45], N and K are the nutrients required in the greatest quantities by most crops and, for this reason, are also the most abundant in plant tissues, reaching values four to five times higher than those accumulated in residues compared to P. In this study, at the 100% rate, the N and K values were 11 and 6 times greater than P, respectively.

In a study evaluating biomass production, macronutrient content, and export in Brassica crops as a function of nitrogen (N) rates, Aquino et al. [55] and Alves et al. [56] reported that macronutrient uptake followed the following decreasing order of export: K > N > Ca > S > P > Mg.

3.2. Physicochemical Attributes

The physicochemical analysis of broccoli revealed no significant differences among the fertilizers and application rates for moisture (MOI), ash (ASH), lipids (LIP), protein (PROT), crude fiber (CF), and amino acids (AA). However, this was not the case for total soluble solids (TSS) and hydrogenionic potential (pH), which showed significantly higher values ($p < 0.05$) where CMP was applied (4.34°Brix) and Org and PCMP (7.18; 7.26), when compared to PCMP and GOF for TSS and CMP for pH, respectively (Table 5).

The P content in the soil can influence several characteristics related to the physical–chemical quality of plants, mainly in the contents of fibers, lipids, proteins, and ascorbic acid, since the deficiency of this nutrient in the soil can reduce plant development, affecting biomass production and, consequently, the concentration of these nutrients [57]. However, this was not observed for these nutrients in this study, as the fertilizers provided P in adequate amounts for plant development.

Analyzing the physicochemical composition of the edible part of broccoli at harvest, Storck et al. [27] reported similar values for MOI (91.2%) and PROT (3.6%), and lower values for ASH (0.8%), LIP (0.03%), and CF (2.9%) compared to those obtained in this study. According to the authors, broccoli is an excellent source of fiber, a condition also observed in this study, where the CF content ranged from 15.02% to 16.25%, further highlighting the common occurrence of high variability in CF content among brassicas (cauliflower and broccoli) and foods in general.

The LIP content in broccoli ranged from 2.27% to 3.54%, PROT from 2.66% to 2.82%, and AA from 15.87% to 20.12%, values that are higher than those obtained by Torres et al. [10] for cauliflower, which reached maximum values of 0.16%, 1.36%, and

5.86%, and for cabbage, which ranged from 0.06%, 1.33%, and 20.0%, highlighting that broccoli is richer in LIP, PROT, and AA compared to cabbage and cauliflower, which together are the most consumed brassicas in the country [6].

Table 5. Bromatological composition of broccoli grown under different fertilizer types and phosphorus application rates in Uberaba, MG, 2024.

Fertilizer	Parameters Evaluated in Broccoli								
	MOI	**ASH**	**LIP**	**PROT**	**CF**	**TTA**	**TSS**	**pH**	**AA**
			%			**Meq L^{-1}**	**°Brix**	**mg 100 g^{-1}**	
					Fertilizer (F)				
CMP	89.28	8.82	3.54	2.77	15.02	0.64	4.34a	6.93b	17.11
PCMP	89.77	8.78	3.13	2.82	16.25	0.61	3.20b	7.26a	20.12
GOF	90.09	8.67	2.27	2.66	15.31	0.67	3.59b	7.18a	15.87
%					Rate (R)				
0	89.96	8.54	3.13	2.66	15.60	0.61b	3.76 b	7.26a	16.95
50	89.71	8.87	3.28	2.78	15.07	0.65b	3.30b	6.99c	15.94
75	89.05	8.52	3.29	2.80	16.25	0.58b	3.50b	7.10b	18.88
100	90.13	9.06	3.55	2.75	15.19	0.72a	4.28a	7.16a	19.03
F-test for F	0.93 ^{ns}	0.16 ^{ns}	7.15 ^{ns}	0.83 ^{ns}	2.08 ^{ns}	1.18 ^{ns}	13.54 *	27.81 **	4.27 ^{ns}
F-test for R	1.82 ^{ns}	2.49 ^{ns}	2.71 ^{ns}	0.70 ^{ns}	1.08 ^{ns}	4.40 *	4.76 *	9.26 **	0.37 ^{ns}
F-test for F x R	0.72 ^{ns}	4.83 ^{ns}	0.84 ^{ns}	2.05 ^{ns}	1.62 ^{ns}	7.71 **	8.74 **	6.81 **	7.17 ^{ns}
CV% for F	1.15	7.63	8.14	11.25	9.98	14.38	14.66	1.59	20.68
CV% for R	1.30	5.66	9.62	7.84	9.90	13.91	15.69	1.56	18.04

* = Significant ($p < 0.01$); ** = Significant ($p < 0.05$); ns = Not significant. Means followed by the same lowercase letter in the column compare attributes within each season, while uppercase letters in the columns compare attributes between seasons, which do not differ according to the Scott–Knott test ($p < 0.05$). CV% = Coefficient of variation; MOI = Moisture; ASH = Ash; LIP = Lipids; PROT = Proteins; CF = Crude fiber; TSS = Total soluble solids; TTA = Total titratable acidity; pH = Hydrogen potential (pH); and AA = Ascorbic acid.

According to Mcdonald et al. [58], vegetables are not natural sources of LIP. Lipids are highly energetic molecules found in plant and animal tissues that act in the organism as electron carriers, substance transporters in enzymatic reactions, components of biological membranes, and as energy reserves. However, this behavior was not observed in this study for broccoli, which showed high LIP contents.

Ornellas [29] reported that broccoli and cauliflower contain between 1.0% and 3.0% protein (PROT), a range also observed in the present study for broccoli. The author further emphasized that these morphologically similar species exhibit nutritional variation depending on the plant part analyzed.

The TSS content in plants refers to the amount of soluble substances present in the sap and can be indirectly affected by the availability of P. In this study, the highest TSS content (4.34°Brix) was obtained in the CMP treatment, probably due to the higher availability of phosphorus in the soil, since this fertilizer has greater solubility and releases nutrients more quickly compared to GOF and PCMP, as also observed by Torres et al. [10]. According to Santos et al. [6], the soluble sugars in fruits and vegetables in combined forms are responsible for sweetness, flavor, and color, which may vary depending on climatic conditions, cultivar, soil characteristics, and the amount of water added during sample processing.

According to Rinaldi et al. [59], TSS levels range from 2 to 5°Brix for brassicas, with their study on minimally processed cabbage reporting levels ranging from 3.67 to 4.25°Brix. This was also observed by Ferreira et al. [28], who obtained a TSS content of 5.56°Brix for white cabbage, and for broccoli, it also fell within this range, ranging from 3.20 to 4.34°Brix.

The pH value of CMP fertilizer (6.93) was significantly lower than that of GOF (7.18) and PCMP (7.26) fertilizers, which had similar values. However, it is known that in very acidic soils (pH below 5.5) or very alkaline soils (pH above 7.5), P can become less available to plants, being fixed or forming insoluble compounds [48], which shows that, even though the CMP value is lower than the others, all are within the range considered normal for the crop [27].

The TTA refers to the amount of acids present in the vegetable and is an important measure for characterizing the quality of broccoli, especially in relation to its freshness and processing. Fernandes et al. [60] point out that, as the harvest period approaches, ATT levels decrease in the plant, a condition not observed in this study.

Regarding the rates, the highest values for TTA (0.72 Meq L^{-1}), TSS (4.28°Brix), and pH (7.16) always occurred at the highest rate evaluated (100%), except for pH, which did not differ from the zero rate (Table 5). This pattern was expected, as at this rate, the plants exhibited the best nutritional status (Table 4).

A significant interaction was observed between fertilizer type and application rate for total titratable acidity (TTA), total soluble solids (TSS), and pH. Regression analysis of the interaction effects revealed a polynomial fit for total titratable acidity (TTA) (Figure 5A), total soluble solids (TSS) (Figure 5B), and pH (Figure 5C). As the fertilizer application rate increased, the values of these parameters decreased to minimums of 0.59 Meq L^{-1}, 3.2°Brix, and pH 7.03 at rates of 32%, 50%, and 52%, respectively, after which they began to increase again with higher application rates.

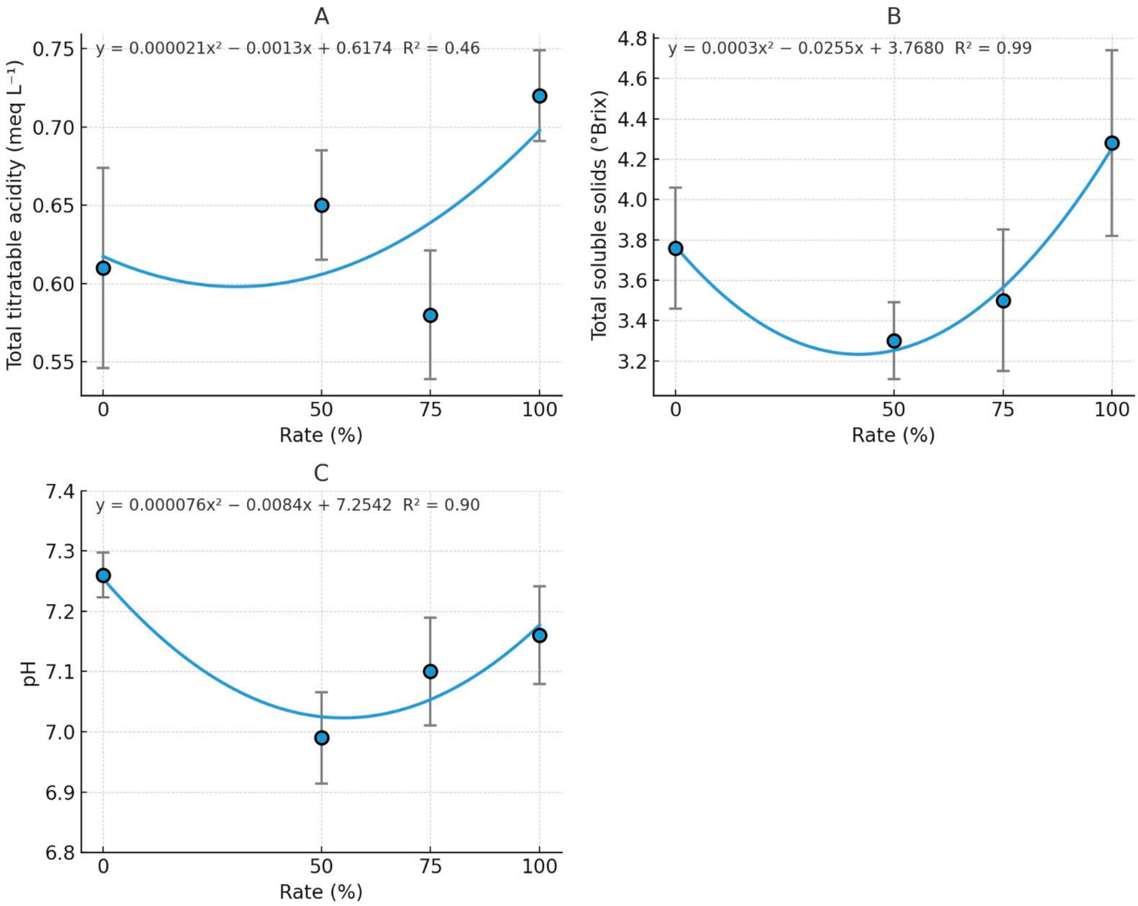

Figure 5. Polynomial regression analysis of the interaction effects on total titratable acidity (TTA) (**A**), total soluble solids (TSS) (**B**), and pH (**C**) in broccoli harvested from the experimental area in Uberaba, MG, 2024.

According to Torres et al. [10], the physicochemical quality of brassicas is directly influenced by climatic factors, the variety and mineral nutrition of the plant, as well as the residues from the cover crops of predecessor plants, which also affect these same bromatological attributes. Fernandes et al. [60] emphasized that citric acid content and overall acidity tend to decrease during the maturation process, increasing pH in certain crops.

4. Conclusions

Granulated organomineral fertilizer (GOF) provided the best agronomic performance (HFM, HDM and YLD) for broccoli and the greatest residual effect in the soil compared to polymerized monoammonium phosphate (PCMP) and conventional monoammonium phosphate (CMP).

The moisture, ash, protein, lipid, total titratable acid and ascorbic acid contents were not significantly ($p < 0.05$) affected by the fertilizers used; on the other hand, total soluble solids and pH showed the highest and lowest values, respectively, with CMP.

The best agronomic performance, the highest phosphorus content in the soil and plant, and the best physicochemical quality of broccoli occurred at a dose of 100% (400 kg ha^{-1} of P_2O_5) of the recommendation for the crop, with the three fertilizers evaluated.

Author Contributions: Conceptualization, M.H.R.F., R.d.C., J.L.R.T. and D.M.d.S.V.; methodology, M.H.R.F., R.d.C., V.O.J., F.A.D.J., C.C.d.O. and J.L.R.T.; software, J.L.R.T., A.L., M.M.A.P.d.M.S. and D.M.d.S.V.; validation, M.H.R.F., R.d.C., J.L.R.T., M.M.A.P.d.M.S.; formal analysis, R.d.C., J.L.R.T. and A.L.; research, D.M.d.S.V. and J.L.R.T.; resources, M.H.R.F. and R.d.C.; data curation, R.d.C., J.L.R.T. and A.L.; writing/preparation of original draft, D.M.d.S.V., J.L.R.T. and R.d.C.; writing/revising and editing, D.M.d.S.V., J.L.R.T., R.d.C., V.O.J., F.A.D.J., M.M.A.P.d.M.S. and A.L.; visualization, D.M.d.S.V. and J.L.R.T.; supervision, M.H.R.F., R.d.C. and J.L.R.T.; project administration, R.d.C. and J.L.R.T.; acquisition of funding, M.H.R.F. and R.d.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The original data presented in the study will be openly available at https://repositorio.ufu.br as soon as the doctoral thesis is defended in the Postgraduate Program in Agronomy.

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Conflicts of Interest: Author Miguel Henrique Rosa Franco was employed by the AGROCP Company. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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