

## Article

# Enhancing Soybean Physiology and Productivity Through Foliar Application of Soluble Monoammonium Phosphate

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**Abstract:** Phosphorus (P) is essential for crop growth, but its complex behavior in tropical soils necessitates alternative management strategies, such as foliar supplementation. Foliar-applied nutrients act as biostimulants, enhancing stress tolerance and plant productivity. This study assessed the physiological responses of soybean to foliar application of soluble monoammonium phosphate (MAP; at a rate of 5 kg ha<sup>-1</sup> each application) at different phenological stages (two during vegetative stages V<sub>4</sub> and V<sub>6</sub> and two during reproductive stages R<sub>1</sub> and R<sub>3</sub> or all four stages) across two growing seasons in tropical field conditions. Key parameters analyzed included leaf nutrient content, photosynthetic pigments, Rubisco activity, carbohydrate content, gas exchange (photosynthetic rate, stomatal conductance, transpiration, water use efficiency, and carboxylation efficiency), oxidative stress markers, and productivity indicators (100-grain weight and grain yield). MAP application improved all parameters, particularly at R<sub>1</sub> and R<sub>3</sub>. Total chlorophyll increased by 29.2% at R<sub>1</sub> and 30.0% when applied at all four stages, while the net photosynthetic rate rose by 15.8% and 18.4%, respectively. Water use efficiency improved by 20.0% at R<sub>1</sub> and all four stages, while oxidative stress indicators, such as H<sub>2</sub>O<sub>2</sub> levels, decreased. Rubisco activity increased most at R<sub>3</sub> (46.0%) and all four stages (59.9%). Grain yield was highest with MAP spread at all four stages (12.3% increase), though a single application at R<sub>1</sub> still boosted yield by 7.4%, compared to the control treatment.

**Keywords:** foliar fertilization; *Glycine max* L. merrill; oxidative metabolism; photosynthesis; soluble monoammonium phosphate



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## 1. Introduction

Soybean is the most important crop cultivated in Brazil, which was responsible for 39% of global soybean production in 2023–2024 [1]. Over the last 20 years, soybean production in Brazil has more than doubled. Although this growth is primarily due to an increase in the planted area, it also reflects an increase in yields of almost 25% due to better genetics and improved crop management practices [2]. These increases notwithstanding, soybean producers are continually evaluating methods and techniques, such as foliar fertilization with phosphorus (P) and nitrogen (N), that can improve crop management and increase yields [3–5].

Nitrogen is a component of proteins, nucleic acids (DNA and RNA), membrane lipids, ATP (energy transfer), NADH, NADPH, co-enzymes, photosynthetic pigments, secondary metabolites, and other organic compounds [6]. Nitrogen is the nutrient required in the greatest quantity by plants, reaching up to 5% of plant dry biomass [7]. Because soybean is a legume, the greatest part of its N demand is supplied by biological nitrogen fixation (BNF) through symbiosis with *Bradyrhizobium* bacteria [8,9]. However, the increases in soybean yield attributable to plant breeding and crop system innovations may create a need for N complementation. Low-dose N foliar application has been shown to be viable for soybeans [10,11].

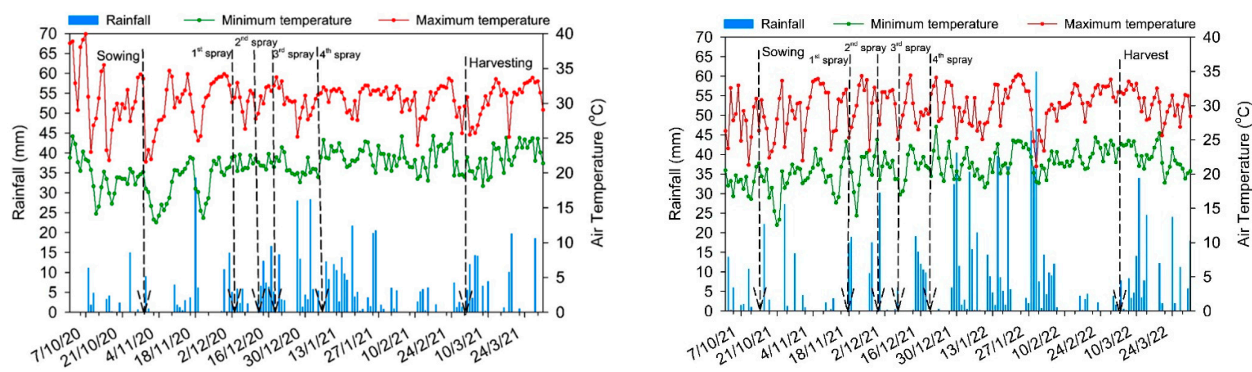
Phosphorus is an essential plant nutrient and is required for many metabolic functions. It is involved in vital processes such as photosynthesis, respiration, energy transfer, nucleic acid synthesis (DNA and RNA), and enzyme activation [12,13]. It also participates in the formation of ATP, the main molecule for energy storage and transfer in cells. Furthermore, P has a key role in the synthesis of phospholipids, which are the main components of cell membranes and are necessary to maintain cell integrity and regulate the transport of nutrients, water, and other molecules in and out of the cell. Few studies have shown the effect of P foliar spray in enhancing photosynthesis and biochemical characteristics in plants [14] and improving fruit quality [15]. P deficiency can lead to stunted growth, reduced biomass production, and, consequently, lower crop yields [16,17]. Tropical crop-lands frequently have weathered soils and high P sorption (P fixation) capacity due to high concentrations of iron and aluminum oxides. These oxides fix P added to the soil before it can be absorbed by crops, resulting in retention of P in the solid fraction of the soil [18,19]. Adequate availability of P is essential for healthy plant growth, as it promotes root development and initial seedling establishment [7,20].

During soybean cultivation, fertilizer is typically applied to the soil, and the nutrients are absorbed by the roots. However, plants can also absorb nutrients through leaves [21–23]. Foliar fertilization can function as a complementary alternative to supply enough nutrients throughout the crop cycle [24,25]. For foliar applications, soluble monoammonium phosphate (MAP), which is formed through the reaction of ammonium with phosphoric acid, can be used as a source of both N and P. This study aimed to evaluate the effect of foliar MAP application at different phenological stages of soybean on photosynthetic pigment content, photosynthetic parameters, oxidative stress indicators, and soybean grain yield.

## 2. Materials and Methods

### 2.1. Site Description

The studies were carried out during the 2020–2021 and 2021–2022 growing seasons at the Lageado Experimental Farm, São Paulo State University (UNESP), in Botucatu in southeastern São Paulo, Brazil (48°26' W, 22°51' S, elevation of 786 m altitude). According to the Köppen-Geiger climatic classification system, the climate in the region is characterized as Cwa, i.e., a humid subtropical climate with dry winters and hot summers [26]. The average rainfall is 1360 mm year<sup>-1</sup>, and the average annual air temperature is 20.7 °C [27]. The soil is classified as an Oxisol [28], which corresponds to a clayey textural class, kaolinitic, thermic Typic Haplorthox [29]. The experimental area is managed under no tillage. The soil characteristics (chemical properties), precipitation, and temperature at the site during the two growing seasons of the experiment are presented in Table 1 and Figure 1.



**Figure 1.** Rainfall and minimum and maximum temperatures during the first and second growing seasons (2020/21–2021/22).

**Table 1.** Soil chemical properties. Lageado Experimental Farm, São Paulo, Brazil.

Attributes	Values	Unit/Extractant
pH	5.2	CaCl <sub>2</sub>
Soil organic matter	24	g dm <sup>-3</sup>
Phosphorus	25	mg dm <sup>-3</sup>
Sulfur	14	mg dm <sup>-3</sup>
Potential acidity [H + Al <sup>3+</sup> ]	31	mmol <sub>c</sub> dm <sup>-3</sup>
Potassium	3.9	mmol <sub>c</sub> dm <sup>-3</sup>
Calcium	38	mmol <sub>c</sub> dm <sup>-3</sup>
Magnesium	11	mmol <sub>c</sub> dm <sup>-3</sup>
Cation exchange capacity	79	CEC <sub>pH 7.0</sub>
Base saturation (BS)	55	%
Iron	13	mg dm <sup>-3</sup>
Copper	1.6	mg dm <sup>-3</sup>
Manganese	15	mg dm <sup>-3</sup>
Zinc	3.0	mg dm <sup>-3</sup>
Boron	0.6	mg dm <sup>-3</sup>
Clay	520	g kg <sup>-1</sup>
Sandy	360	g kg <sup>-1</sup>
Silt	120	g kg <sup>-1</sup>

## 2.2. Experimental Design and Treatment Descriptions

A randomized complete block design (RCBD) was used with four replicates for each treatment. The six treatments differed in the physiological stage at which soluble monoammonium phosphate (MAP 12-61-00) was sprayed on the leaves of soybean:

- (I) Control (no treatment);
- (II) Foliar spraying of soluble MAP at the V<sub>4</sub> vegetative phenological stage [30];
- (III) Foliar spraying of soluble MAP at the V<sub>6</sub> vegetative phenological stage [30];
- (IV) Foliar spraying of soluble MAP at the R<sub>1</sub> reproductive phenological stage [30];
- (V) Foliar spraying of soluble MAP at the R<sub>3</sub> reproductive phenological stage [30];
- (VI) Foliar spraying of soluble MAP in all phenological stages—V<sub>4</sub>, V<sub>6</sub>, R<sub>1</sub>, and R<sub>3</sub>.

Spraying was carried out using a backpack sprayer propelled by CO<sub>2</sub> at a constant pressure of 1.8 bar. The sprayer was equipped with a spray boom containing 6 flat fan nozzles (TTI 110 02 VP TeeJet) with a spacing of 0.50 m between nozzles. The soluble MAP rate used for foliar application was 5 kg ha<sup>-1</sup>, which corresponds to 3.1 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> and 0.55 kg ha<sup>-1</sup> of NH<sub>4</sub><sup>+</sup>. An organosilicon adjuvant (polydimethylsiloxane, d = 1.1 g cm<sup>-3</sup>) was added at a rate of 30 mL ha<sup>-1</sup> to improve spray performance, and the spray volume rate was 150 L ha<sup>-1</sup> for each treatment.

### 2.3. Management Practices

The soybean cultivar was NEO 580 IPRO. The seeds were treated previously with fungicides (100 g a.i. carboxin + 100 g a.i. thiram 100 kg<sup>-1</sup> seeds) and inoculated with SEMIA 5079 (*Bradyrhizobium japonicum*) and SEMIA 5080 (*Bradyrhizobium diazoefficiens*) [31,32]. Mechanized sowing was performed to obtain a population of approximately 330,000 plants ha<sup>-1</sup>. Fertilization management consisted of 80 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> as base fertilization and 70 kg ha<sup>-1</sup> of K<sub>2</sub>O applied in topdressing for both growing seasons. Each plot consisted of 10 rows with an inter-row spacing of 0.45 m and a row length of 10 m, corresponding to an area of 45 m<sup>2</sup>. Weed, pest, and disease management was carried out when necessary, following the recommendations [33].

### 2.4. Nutritional Analyses (Crop Nutrition)

To assess the nutritional status of soybean plants, the third fully expanded leaf with petiole from the apex to the base was sampled from 20 plants per plot at the R<sub>3</sub> phenological stage (beginning of pod formation) [34]. The N concentration in the plant material was determined by sulfuric-perchloric acid digestion and the Kjeldahl distillation method. The concentrations of potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), and zinc (Zn) in the leaves were measured by atomic absorption spectrometry after nitroperchloric digestion. Additionally, the concentration of P in the leaves was determined by colorimetry [35].

### 2.5. Photosynthetic Pigments and Enzyme

To quantify photosynthetic pigments (chlorophyll *a*, chlorophyll *b*, total carotenoids, and total chlorophylls), five discs with a diameter of 0.5 cm were cut from the last fully expanded leaf, between the edge and midrib. These samples were stored for 24 h in glass vials wrapped in aluminum foil and containing 2 mL of N,N-dimethylformamide (DMF) [36]. Pigment contents were quantified spectrophotometrically at wavelengths of 664 nm for chlorophyll *a*, 647 nm for chlorophyll *b*, and 480 nm for carotenoids [37].

To quantify ribulose-1,5-bisphosphate carboxylase/oxygenase enzyme activity (Ru-bisco), the third fully expanded leaf without petiole was collected at the R<sub>4</sub> phenological stage [30]. Rubisco activity was calculated from the difference between absorbance readings obtained at 0 and 1 min (without removing the cuvette from the spectrophotometer) and expressed in μmol min<sup>-1</sup> mg protein<sup>-1</sup> [38].

### 2.6. Gas Exchange Parameters

To determine gas exchange parameters, a portable infrared gas analyzer (CIRAS-3 Portable Photosynthesis System, PP Systems Inc., Amesbury, MA, USA) was used. The parameters were 380–400 mol mol<sup>-1</sup> atmospheric CO<sub>2</sub>, 1100 μmol quanta m<sup>-2</sup> s<sup>-1</sup> of photosynthetically active radiation (PAR) supplied by LED lamps, 25–27 °C leaf chamber temperature, and 60–70% relative humidity. The measurements were performed at the R<sub>4</sub> phenological stage using the central intact leaflet of the third fully expanded leaf from the plant apex on the main stem. The following parameters were determined: net photosynthetic rate (*A*; μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>), stomatal conductance (*G*<sub>s</sub>; mol H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>), internal CO<sub>2</sub> concentration in the substomatal cavity (*C*<sub>i</sub>; μmol mol<sup>-1</sup>), and transpiration (*E*; mmol H<sub>2</sub>O m<sup>-2</sup> s<sup>-1</sup>). The water use efficiency (WUE; μmol CO<sub>2</sub> (mmol H<sub>2</sub>O)) was calculated as the *A*/*E* ratio, and the carboxylation efficiency was calculated as the *A*/*C*<sub>i</sub> ratio. The measurements were performed between 9:00 and 11:00 a.m.

### 2.7. Total Soluble Sugar Concentration

The total soluble sugar concentration was determined by the sulfur phenol method, which consists of using sulfuric acid to dehydrate simple sugars and form complexes with phenol, changing the color of the solution. This color change, measurable in the visible spectrum, is directly proportional to the total sugar content in the sample [39]. The concentrations were determined by comparing them to a standard sucrose curve and expressed in  $\text{g kg}^{-1}$ .

### 2.8. Oxidative Stress and Antioxidant Enzymes

The same leaves used for Rubisco determination were used to measure the levels of hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) and malondialdehyde (MDA) and the activities of superoxide dismutase (SOD; EC: 1.15.1.1), catalase (CAT; EC:1.11.1.6), and ascorbate peroxidase (APX; EC:1.11.1.11).

Malondialdehyde content (Lipid peroxidation) was calculated using a molar extinction coefficient of  $155 \text{ mM}^{-1} \text{ cm}^{-1}$  and expressed in  $\text{nmol MDA g}^{-1}$  fresh weight [40].  $\text{H}_2\text{O}_2$  content was calculated based on a calibration curve and expressed in  $\mu\text{mol H}_2\text{O}_2 \text{ g}^{-1}$  fresh weight [41]. Superoxide dismutase (SOD) activity was quantified and expressed in units (U) of SOD  $\text{mg}^{-1}$  protein [42]. Catalase (CAT) activity was measured and expressed in  $\mu\text{mol min}^{-1} \text{ mg}^{-1}$  protein [43]. Ascorbate peroxidase (APX) activity was determined and expressed in  $\text{nmol min}^{-1} \text{ mg}^{-1}$  protein [44].

### 2.9. Agronomic Parameters and Grain Yield

In both growing seasons (2020–2021 and 2021–2022), 100-grain weight and grain yield were determined. For grain yield, the soybean plants in 2 m sections of each of 4 rows were harvested ( $1.8 \text{ m}^2$ ), threshed, and weighted. The weight was adjusted to 13% moisture and then converted to  $\text{kg ha}^{-1}$ . The 100-grain weight was determined by counting 10 samples of 100 grains, which were weighed and adjusted to 13% moisture

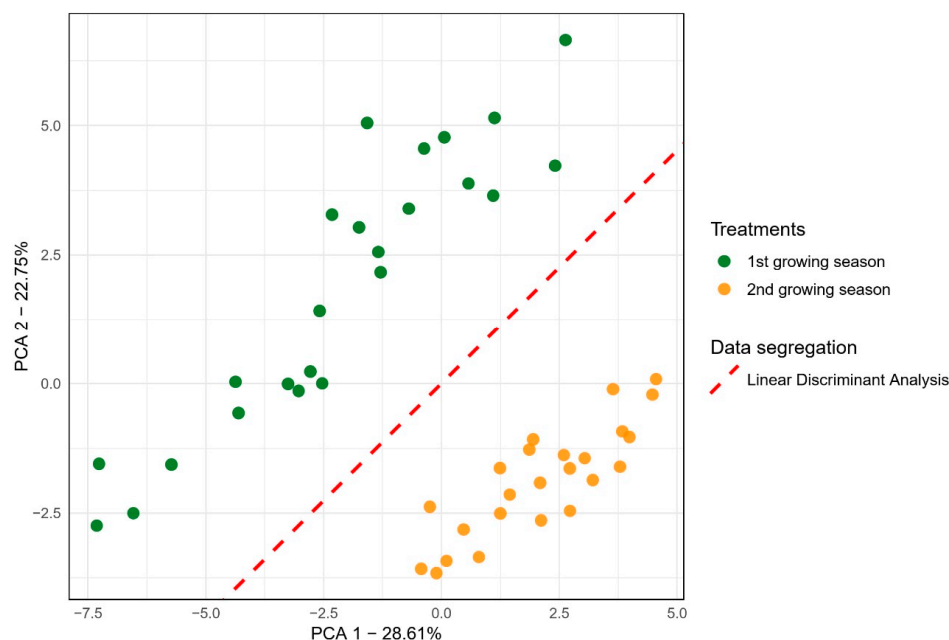
### 2.10. Statistical Analysis

The data collected from both studies were subjected to normality [45] homoscedasticity [46] analyses. Next, statistical analysis was performed using a double factorial design (treatments vs. growing seasons). The first factor was the application of soluble MAP, and the second factor was the growing season (2020–2021 or 2021–2022). The data were then analyzed by one-way analysis of variance (ANOVA), and the significance of differences was assessed using the least significant difference (LSD) test at a significance level of 5%. This analysis is summarized in the Supplementary Material. No significant effects of growing seasons or interactions between factors were observed, and the averages of the two growing seasons are presented for each treatment. All statistical analyses were performed using the statistical software Sisvar<sup>®</sup>, and the figures were generated using SigmaPlot version 15.0.

## 3. Results

The principal component analysis—PCA (Figure 2)—revealed a clear separation between the two growing seasons, indicating that variables related to environmental conditions, such as temperature, precipitation, and water availability, played a determining role in the crop's performance each growing season. Precipitation was 30% higher in the second growing season than in the first growing season, a difference that can be very significant for a rainfed field in a tropical country. Based on this analysis, it was decided to present the consolidated data as the average of the two agricultural years in the subsequent sections. This approach highlights the general trends of the applied treatments and mitigates

interannual variability, providing a more robust view of the treatments' behavior over the evaluated period.



**Figure 2.** Principal component analysis (PCA) between the first (2020–2021) and second (2021–2022) growing seasons.

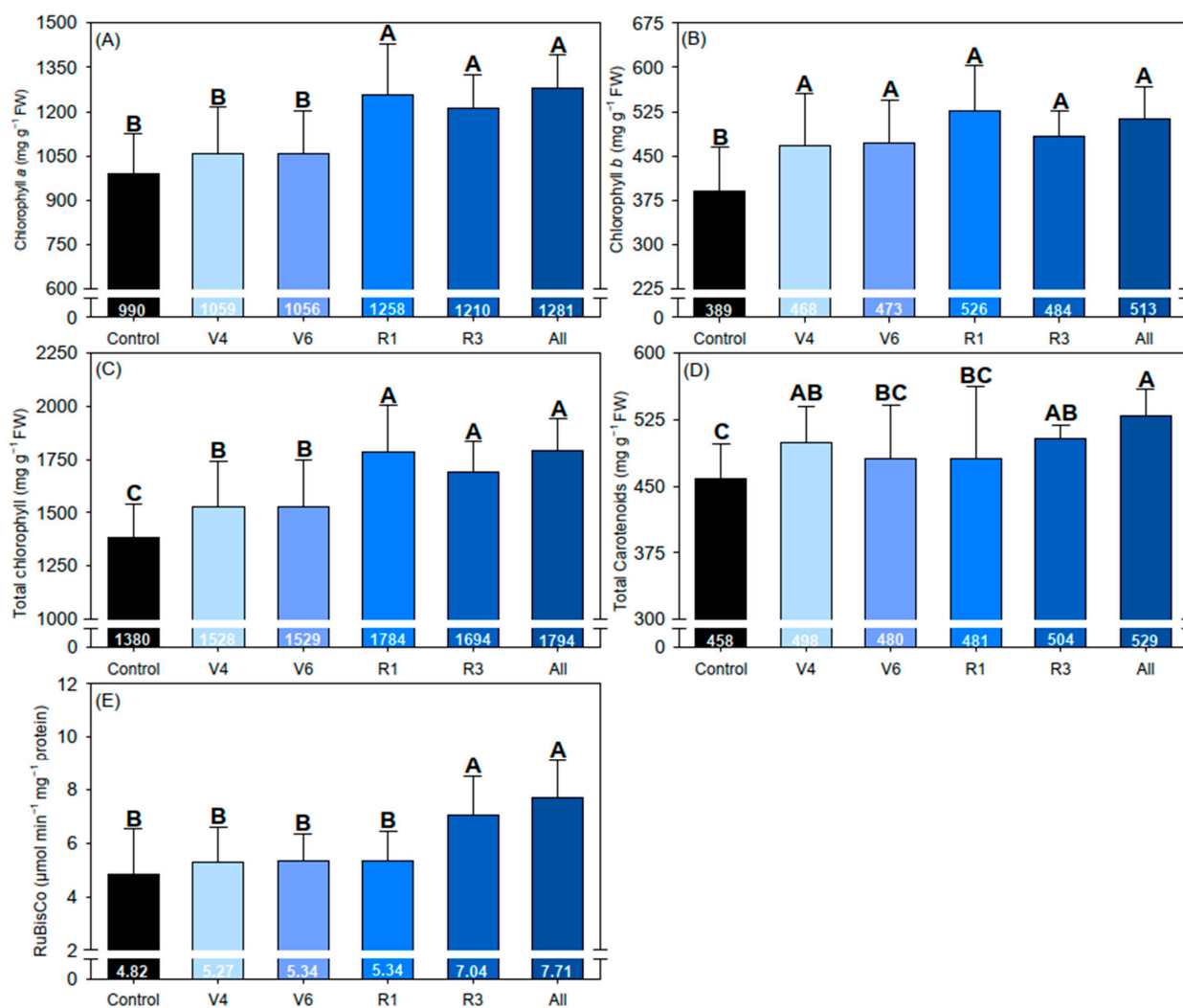
There were few variations in leaf nutrient content between the MAP foliar application treatments and the control. For nutrients that differed, the concentration was always higher in the treatment with MAP than in the control (non-sprayed) (Supplementary Table S1). Despite the differences noticed, all elements are within the ranges proposed for soybean crops [31].

The applications in R<sub>1</sub>, R<sub>3</sub>, and MAP All increased chlorophyll *a* content by 27.1%, 22.2%, and 29.4%, respectively (Figure 3A). All of the treatments increased chlorophyll *b* and total chlorophyll contents compared with the control, but the increases were largest in R<sub>1</sub>, R<sub>3</sub>, and MAP All (Figure 3B,C). Compared with the control, all treatments increased total carotenoid content, which was highest in MAP All (Figure 3D). R<sub>3</sub> and MAP All increased Rubisco activity by 46.1% and 60.0%, respectively, compared with the control (Figure 3E).

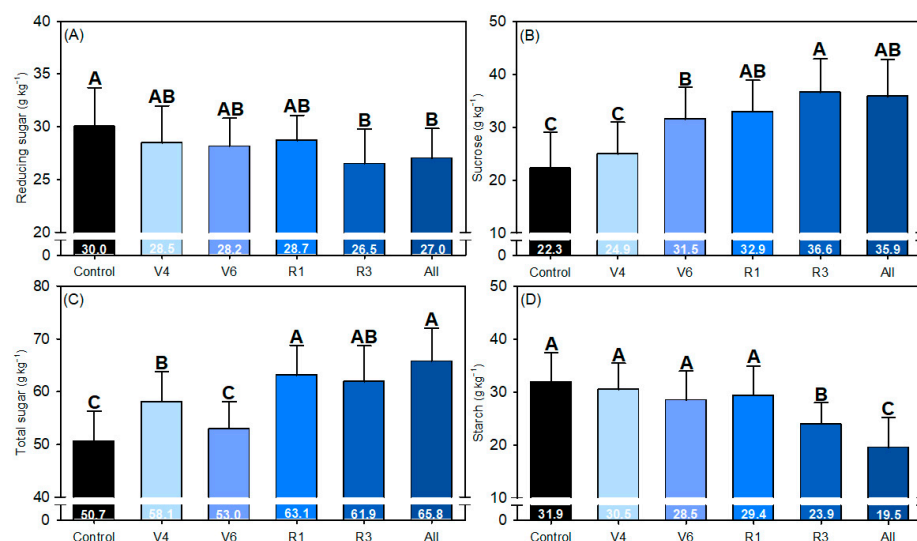
Compared with the control, sugar content decreased the most in R<sub>3</sub> (11.7%) and MAP All (Figure 4A). R<sub>3</sub>, MAP All, and R<sub>1</sub> increased sucrose content by 64.1%, 61.0%, and 47.0%, respectively (Figure 4B), whereas MAP All and R<sub>1</sub> increased total sugar content by 29.8% and 24.5%, respectively (Figure 4C). MAP All was most effective in reducing starch content, decreasing it by 38.9% compared with the control (Figure 4D).

Among photosynthetic parameters, *A*, *g<sub>s</sub>*, and WUE were highest in MAP All (Figure 5A,B,D). *C<sub>i</sub>* was lowest in R<sub>3</sub> and MAP All, with decreases of 5.4% in both treatments compared with the control (Figure 5C). R<sub>3</sub> and MAP All also had the largest effects on *A/C<sub>i</sub>*, increasing it by 21.4% and 25%, respectively, compared with the control (Figure 5E). *E* did not differ significantly between the treatments and the control.

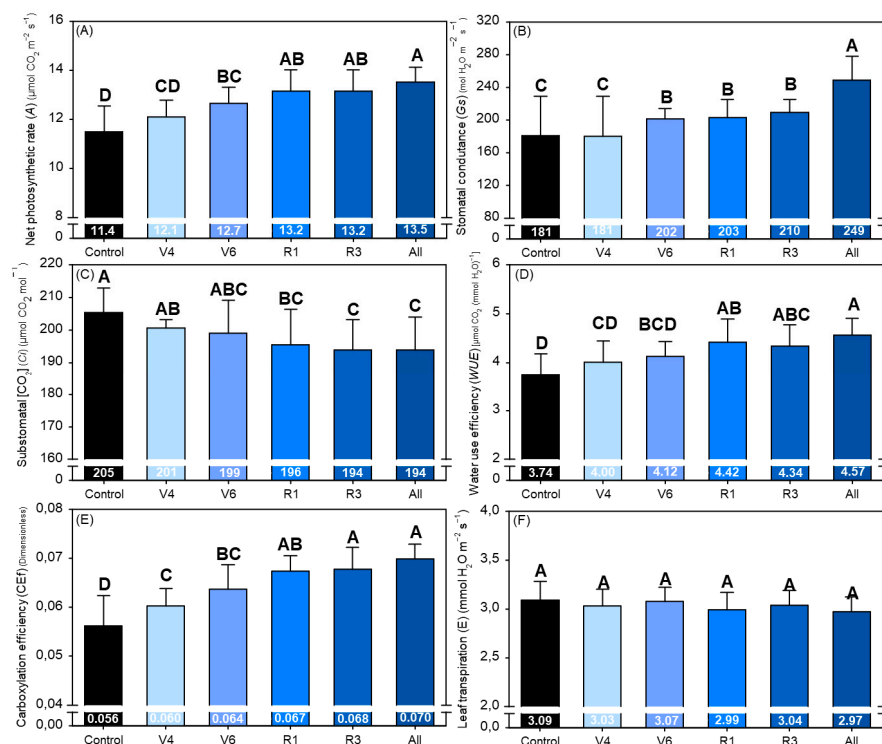
MAP application, particularly MAP All, reduced all oxidative stress indicators (Figure 6). The concentration of H<sub>2</sub>O<sub>2</sub> decreased by 28.0% and 27.3% in R<sub>1</sub> and MAP All, respectively, compared with the control (Figure 6A). MDA content, superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX) activities, and proline content were 26.1%, 12.5%, 54.5%, 29.2%, and 18.9% lower, respectively, in MAP All than in the control (Figure 6B–F).



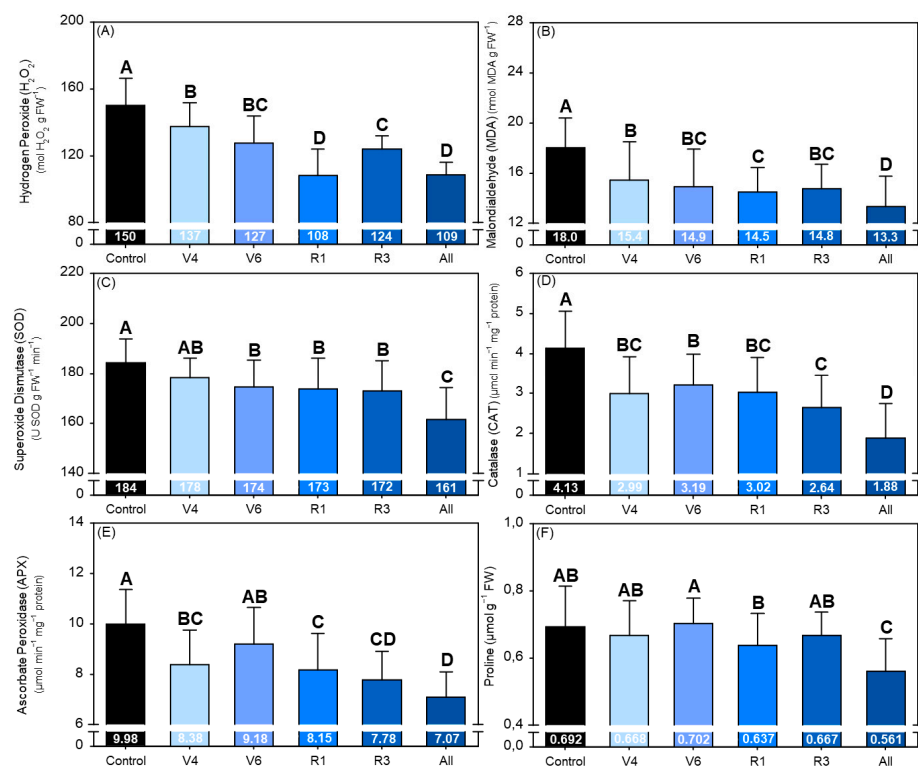
**Figure 3.** Chlorophyll *a*, chlorophyll *b*, total chlorophyll, total carotenoids, and Rubisco (A–E) levels in soybean plants sprayed with MAP in different phenological stages. Bars for the same parameter and growing season with different letters are significantly different by Fisher's protected LSD test at  $p \leq 0.05$ .



**Figure 4.** Reducing sugar, sucrose, total sugar, and starch (A–D) contents in soybean plants sprayed with MAP in different phenological stages. Bars for the same parameter and growing season with different letters are significantly different by Fisher's protected LSD test at  $p \leq 0.05$ .

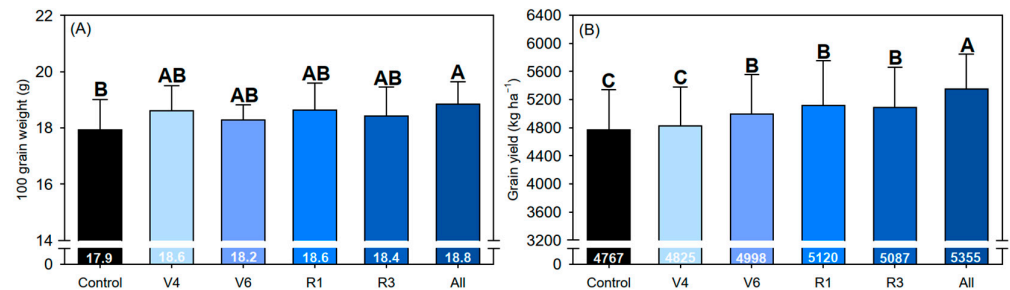


**Figure 5.** Net photosynthetic rate (A), stomatal conductance (gs), substomatal  $\text{CO}_2$  concentration ( $\text{Ci}$ ), water use efficiency (WUE), carboxylation efficiency (A/Ci), and leaf transpiration (E) (A–F) of soybean plants sprayed with MAP in different phenological stages. Bars for the same parameter and growing season with different letters are significantly different by Fisher’s protected LSD test at  $p \leq 0.05$ .



**Figure 6.** Hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) content; malondialdehyde (MDA) superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) activities; and proline content (A–F) of soybean plants sprayed with MAP in different phenological stages. Bars for the same parameter and growing season with different letters are significantly different by Fisher’s protected LSD test at  $p \leq 0.05$ .

These improvements were reflected in soybean yield (Figure 7). MAP All had the best performance with respect to 100-grain weight and grain yield. All MAP treatments increased 100-grain weight, but MAP All increased 100-grain weight by 5.0% compared with the control (Figure 7A). Grain yield did not differ between V<sub>4</sub> and the control, but all other MAP treatments increased grain yield (Figure 7B). MAP All resulted in superior performance, increasing grain yield by 12.3% compared with the control.



**Figure 7.** The 100-grain weight and grain yield (A,B) of soybean plants sprayed with MAP in different phenological stages. Bars for the same parameter and growing season with different letters are significantly different by Fisher's protected LSD test at  $p \leq 0.05$ .

#### 4. Discussion

Soluble MAP foliar spraying has become a very common supplementary fertilization practice adopted by farmers to supply N and P to crops, especially soybean plants. The macronutrients P and N play fundamental roles in plant metabolism and are directly related to protein synthesis, photosynthesis, energy storage, and DNA and RNA synthesis [47,48]. The foliar application of these nutrients is a viable option to improve fertilizer use efficiency. Numerous studies have demonstrated that foliar fertilization with N and P not only increases nutrient use efficiency but also reduces losses compared to soil applications because the nutrient is supplied directly to the leaves, where it is absorbed and translocated to the rest of the plant [13,16,18,49]. However, several studies have shown that nutritionally deficient plants do not absorb foliar-applied fertilizers as efficiently as well-nourished plants [3,24,50]. In addition, several studies have demonstrated positive effects of the separate foliar application of N [6,51], but few have studied the combined application of these two nutrients.

The efficiency of P and N use by plants is affected by various physiological processes, and low availability of these nutrients can lead to deficient plants with low concentrations of nutrients in their leaves [13,52]. In this study, foliar levels of P and N did not differ between the treatments and were within an adequate range for soybean cultivation [53]. This can be explained by the dilution effect—the exogenous application of a small amount of nutrient is not enough to increase foliar levels due to the large amount of dry matter [24]. Well-nourished plants are more likely to express their maximum genetic potential and have a greater ability to absorb foliar fertilizers [54]. In an analysis of the permeability of foliar-applied P in wheat plants, the deficiency altered the surface structure and functioning of leaves, with fewer stomata and trichomes on both the adaxial and abaxial sides, making them less permeable to foliar-applied P [55].

Our results showed that foliar application of MAP did not affect foliar nutrient levels but increased chlorophyll content, which is related to the increased supply of N and P in later phenological stages [19]. Chlorophyll and accessory pigments absorb light energy for photosynthesis and are considered non-limiting in the photosynthetic process unless the plant is experiencing some degree of nutrient deficiency [56]. Although N levels did not differ between the treatments, foliar chlorophyll content is directly related to foliar nutrient levels and the synthesis of reducing sugars and sucrose, which is directly proportional

to photosynthetic activity and carbohydrate transport [57], consistent with our results. The high starch concentration in the control treatment reflects the roles of P in regulating metabolic pathways and sugar transport. Sugar transport to the cytoplasm, where sucrose is synthesized, requires a sufficient concentration of P in the chloroplast, and a lack of N can increase starch concentrations in leaves [14,15,57].

Nitrogen and P deficiencies reduce the photosynthetic capacity of plants because N is an essential component of several critical molecules in the photosynthetic process, such as chlorophyll, enzymes, and proteins involved in photosynthesis [14]. Phosphorus is essential for many functions during plant growth and development but is particularly critical for the storage and transfer of energy in the form of ATP and ADP. A lack of P results in low availability of inorganic phosphate ions as an energy substrate for ATP synthesis [50,52]. In addition, P is highly important as a structural component of nucleic acids, coenzymes, phospholipids, and nucleotides, most of which are involved in the photosynthetic process [7,52].

Our results showed that the foliar application of MAP during the reproductive stages of soybean plants or at all developmental stages increased  $A$ ,  $g_s$ ,  $WUE$ , and  $A/C_i$  and reduced  $C_i$ , which can be explained by greater activity of Rubisco, the enzyme responsible for assimilating atmospheric  $CO_2$  [58]. The application of MAP resulted in higher  $A$  and  $g_s$  in well-nourished plants with P, indicating that foliar nutrient application can increase  $A$  and  $g_s$ . The increase in  $A$  can be explained by the increase in chlorophyll levels, as plants with higher pigment concentrations are more photosynthetically active. The improvement in  $WUE$  is related to the improvement in  $A$  since  $WUE$  is the ratio of  $A$  to  $E$  ( $A/E$ ).

Cultivated plants are subjected to various abiotic stresses, including extreme temperatures, drought, nutrient deficiency, salt stress, and even heavy metals, which can trigger the uncontrolled production of reactive oxygen species (ROS). The main forms of ROS produced are  $O_2^-$  and  $H_2O_2$  [59]. The plant antioxidant system, which includes enzymes such as SOD, CAT, and APX, protects against the harmful effects of these ROS by helping to eliminate these toxic substances [44].

In the present study, the plants in the control treatment had higher contents of  $H_2O_2$  and MDA than the plants that were treated with MAP. Consequently, SOD, CAT, and APX activities were higher in the control treatment, as these enzymes were needed to neutralize the toxic effects of ROS. SOD converts singlet oxygen ( $O_2^-$ ) into  $H_2O_2$ , and CAT and APX convert  $H_2O_2$  to  $H_2O$  [60]. However, soybean productivity is compromised when air temperatures exceed  $30\text{ }^\circ\text{C}$ , which may indicate that high temperatures can cause thermal stress in plants [33]. During both soybean growing seasons, air temperatures exceeded  $30\text{ }^\circ\text{C}$  several times, likely causing heat stress in the plants. Periods without rain are also common during soybean cultivation in tropical regions, limiting water availability for plants and potentially causing water stress [61].

Even with environment-limiting factors, the treatments in which MAP was sprayed had a better yield performance compared to the control, except when sprayed at  $V_4$ . The yield increase, especially in MAP All, is likely due to an improvement in the parameters previously discussed. Therefore, MAP foliar application cannot be used to replace fertilization and can play an important role in mitigating plant stresses, which can lead to a higher yield.

## 5. Conclusions

Foliar application of soluble MAP greatly improved photosynthetic parameters and enzyme activities, leading to greater grain yield, especially when MAP was sprayed during the reproductive stages of soybean plants. Nitrogen and phosphorus are essential for plant growth and development. Although foliar application of MAP has beneficial effects, it

cannot replace traditional fertilization. However, foliar spraying allows application to be scheduled during crucial periods of crop development, and MAP is a good option for fertilization because it contains both P and N.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy15040818/s1>.

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## Abbreviations

The following abbreviations are used in this manuscript:

MAP	Monoammonium phosphate
A	Net photosynthetic rate
gs	Stomatal conductance
Ci	Internal CO <sub>2</sub> concentration in the substomatal cavity
E	Transpiration
WUE	Water use efficiency
ROS	Reactive oxygen species
H <sub>2</sub> O <sub>2</sub>	Hydrogen peroxide
MDA	Malondialdehyde
SOD	Superoxide dismutase
CAT	Catalase
APX	Ascorbate peroxidase

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