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Article

Organomineral foliar application modulates photosynthetic pigments and biochemical responses in black mung bean

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Abstract: The use of organomineral products in agriculture offers promising solutions for crop productivity and sustainability. This study examines the effects of foliar application of a biostimulant containing *Ascophyllum nodosum* algae extract and a blend of amino acids on black mung bean (*Vigna radiata* L.), focusing on its potential to modulate beneficial biochemical responses. Under greenhouse conditions, total chlorophyll content was 20% higher (198 µg/g) in treated plants than in untreated controls (167 µg/g). Carotenoid concentrations were also higher (115 µg/g) in treated plants compared to 98 µg/g in the control plants. Considering redox system enzymes, catalase (4180 nmol/µg), peroxidase (6656 nmol/µg), and superoxide dismutase (5546 nmol/µg) activities were lower in treated plants compared to untreated ones (6982 nmol/µg for catalase, 9635 nmol/µg for peroxidase, and 10,403 nmol/µg for superoxide dismutase). However, given the higher levels of photosynthetic pigments observed in treated plants, antioxidant activity may be primarily attributed to non-enzymatic mechanisms, such as carotenoids, which were also elevated relative to controls. These findings demonstrate the potential of the organomineral as a tool for the physiological management of agriculturally important crops, particularly black mung bean. In this context, its adoption holds the potential to significantly improve agricultural productivity and crop resilience.

Keywords: *Vigna radiata*; chlorophyll; antioxidant system; physiological management

1. Introduction

The black mung bean (*Vigna radiata* (L.) R. Wilczek) is a legume native to India but is widely consumed as a food source in many countries, particularly across South and Southeast Asia, and to a lesser extent in certain African nations. This legume has significant nutritional value, being a rich source of proteins, carbohydrates, and minerals [1,2].

India, China, Myanmar, Indonesia, Thailand, Kenya, and Tanzania are the leading producers of black mung beans, contributing an estimated global production of approximately 5 million tons per year [2]. However, despite their high productivity, these countries, located in the Indo-Pacific and East African regions, are also among the world's largest consumers. Consequently, domestic demand surpasses local supply, necessitating imports from other markets to meet consumption needs.

In this context, in 2023, the Brazilian Trade and Investment Promotion Agency (APEX) and the Brazilian Institute of Beans and Pulses (IBRAFE) established strategic initiatives aimed at strengthening trade relations between Brazil and India for the export of this legume. Considering Brazil's production potential, estimated at a minimum of 2.5 million tons per year, this initiative seeks to expand the country's presence in this market and establish more advantageous trade agreements [3].

The use of biostimulants, such as foliar organominerals, has grown significantly in recent years, as these products contribute to more productive and sustainable crops [4]. Their application as abiotic stress mitigators has become even more relevant in the current scenario of climate change, as biostimulants can modulate plant defense mechanisms and increase their tolerance to adverse conditions [5].

Biostimulants are formulated from natural substances that, when applied to plants, promote growth and development, as well as enhance resistance to both biotic and abiotic stresses [6]. These compounds also improve nutrient absorption and stimulate root growth, increasing the ability of plants to explore the soil in search of essential resources [7]. Additionally, they act in the biosynthesis of enzymes, hormones, and chlorophyll, as well as in the transport and storage of nitrogen, thereby playing a crucial role in plant physiology [8].

The application of natural extracts provides plants with physiological benefits related to hormonal balance and osmoprotection, which are essential for maintaining cellular integrity. These compounds protect against dehydration and preserve metabolic activity, even under adverse conditions [9]. Among these substances, algal extracts are known to confer high resistance to osmotic stress, reduce protein degradation, and prevent chloroplast oxidation. This effect contributes to delaying leaf senescence, thereby prolonging plant photosynthetic activity. Additionally, algal extracts enhance nutrient absorption, particularly when applied under suboptimal growth conditions or environmental stress [10,11].

Brown algae of the species *Ascophyllum nodosum* are widely used in agriculture as a natural source of macro- and micronutrients, as well as organic compounds such as amino acids, betaines, alginic acids, and lipids [12]. Thanks to this rich composition, *A. nodosum* has been extensively explored as a foundation for biostimulant development. These algae contribute to enhanced plant growth and productivity, and also function as natural regulators of biochemical and molecular processes, improving plant tolerance to both abiotic and biotic stresses [13].

As the demand for agriculture continues to rise, ongoing efforts are being made to develop and enhance strategies to reduce the impacts of production [14]. Reactive oxygen species (ROS), including superoxide, hydrogen peroxide, and hydroxyl radicals, play a central role in this process. When present in excess, they disrupt cellular metabolism, damage proteins and lipids, compromise membrane integrity, and cause double-strand breaks in DNA. This imbalance increases the risk of mutations and can ultimately hinder plant growth and resilience [15–18].

In light of the growing demand for sustainable agricultural solutions, black mung beans stand out not only for their economic importance but also for their nutritional and social value. In this context, the development and application of innovative technologies are crucial for increasing productivity without compromising environmental sustainability. This study assessed the effects of foliar application of an

organomineral formulated with *A. nodosum* algae extract and a blend of amino acids on black mung beans and investigated its ability to modulate favorable biochemical responses. These responses may represent effective strategies for mitigating productivity losses and optimizing the physiological performance of this crop in sustainable agricultural systems.

2. Materials and methods

2.1. Plant preparation and application

The experiments were conducted using the product Domínio® (Sintese Agro Science LTDA, Maringá, Paraná, Brazil), in compliance with Ordinance No. 104/108 of 20 November 2017, issued by the Ministry of Agriculture, Livestock, and Food Supply of Brazil. This product is a class A organomineral foliar fertilizer derived from *A. nodosum* extract and amino acid blends. Its composition is as follows: Nitrogen (N) 1.30%, Phosphorus (P_2O_5) 3.0%, Potassium (K_2O) 2.0%, Magnesium (Mg) 1.0%, Boron (B) 0.5%, Manganese (Mn) 0.5%, Molybdenum (Mo) 0.1%, Zinc 2.0%, and Total Organic Carbon 6.0%.

The experiment was conducted in a greenhouse at Sintese Agro Science® (23°26′56.9″ S, 51°59′55.4″ W). The plants were grown in 1.7 L pots, filled with soil consisting of 47% clay, 51% sand, and 2% silt, with phosphorus and potassium concentrations of 4.98 mg dm^{-3} and 0.04 cmolc dm^{-3}, respectively. Fertilization was adjusted to an equivalent rate of 300 kg ha^{-1} using a 4-30-10 (N-P_2O_5-K_2O) formulation, which corresponded to approximately 2 g of fertilizer per pot.

Four black mung bean seeds were sown in each pot at a depth of 2 cm. Thirty days after sowing, foliar application of the biostimulant (Domínio®) was carried out at a dose of 0.4 L ha^{-1} (according to the product guidelines). The spray mixture was applied using a CO_2-pressurized backpack sprayer with a fixed boom, equipped with an ADGA 02-type nozzle (medium droplet size), and an application rate of 100 L ha^{-1}. The application was conducted under environmental conditions of 32.2 °C and 49.2% relative humidity, with a spraying speed of 6.1 km/h.

The control treatment consisted of water only under the same conditions. The experiment followed a completely randomized design, with two treatments and four replicates, totaling eight pots. Each replicate consisted of a pot containing four plants. After application, all plants were maintained under greenhouse conditions with regular irrigation. A surface drip irrigation system was used in the experiment, with one emitter per pot and a daily flow rate of 1.0 L h^{-1}. The emitters were programmed to irrigate every 8 h for 10 min per cycle. Ambient temperature was monitored using a digital thermometer.

2.2. Extraction and quantification of chlorophyll and carotenoids from leaves and leaf green area

Three extractions were performed: the first before the application of the treatments described in Section 2.1, the second seven days after application, and the third 14 days after application. In all samplings, the third trifoliate leaf (counting from the top down) was collected and subsequently washed with distilled water to remove

impurities. Then, 100 mg of plant material were macerated in a 20% acetone solution and incubated for 30 min at 20 °C. After the incubation period, the material was homogenized using a vortex mixer and centrifuged at 10,000 g for 15 min. The samples were read for the quantification of photosynthetic pigment levels immediately after the centrifugation process. The quantification of total chlorophyll (Chlt), chlorophyll a (Chla), and chlorophyll b (Chlb) was performed by spectrophotometric reading of the supernatant at wavelengths of 663.2 nm and 646.8 nm. For total carotenoids, absorbance was measured at 470 nm. The concentrations of photosynthetic pigments were calculated based on the equations of Lichtenthaler and Buschmann [19] and expressed in µg/g of plant tissue. The percentage of green cover was determined by analyzing plant images using Canopeo© software (version 1.0) (http://www.canopeoapp.com).

2.3. Extraction and quantification of total proteins and antioxidant enzymes

Extractions were performed at the same time points described in Section 2.2 (before application, seven days after application, and 14 days after application). After washing the plant material with distilled water, 100 mg of tissue was macerated and homogenized in 50 mM potassium phosphate buffer (pH 7.0), containing 1 mM ethylenediaminetetraacetic acid (EDTA) and 1% polyvinylpyrrolidone (PVP). Immediately after maceration, the homogenate was centrifuged at 4 °C at 10,000 g for 15 min. The supernatant was transferred to microtubes and stored at −20 °C until total protein quantification and antioxidant enzyme assays.

2.3.1. Total proteins

The enzymatic extracts were analyzed for total protein content using the Bradford method, which is based on the interaction of Coomassie Brilliant Blue G-250 dye with proteins. Sample absorbance was measured using a spectrophotometer at 595 nm. Protein concentration was determined from a standard curve constructed with bovine serum albumin (BSA) at concentrations of 0.2, 0.4, 0.6, 0.8, and 1.0 mg/mL, with a determination coefficient (R^2) of 0.99.

2.3.2. Catalase (CAT) activity

Catalase activity was quantified by reacting 100 µL of the enzymatic extract with 1 mM hydrogen peroxide (H_2O_2), followed by incubation for 4 minutes at 28 °C. After this period, the reaction was halted by adding 32 mM ammonium molybdate, and absorbance was measured at 405 nm. Enzymatic reaction controls were performed by adding ammonium molybdate prior to the enzymatic extract. Catalase activity was calculated using the molar extinction coefficient (ε) of 40 M^{-1} cm^{-1}, and the results were expressed in nmol/min/µg of protein.

2.3.3. Peroxidase (POX) activity

Peroxidase activity was determined in a reaction mixture containing 50 mM potassium phosphate buffer (pH 7.0), 10 mM hydrogen peroxide (H_2O_2), and 50 mM guaiacol, to which 100 µL of enzymatic extract was added. After a 30-second incubation period at 28 °C, absorbance was monitored at 470 nm for 2 min, with readings recorded every 5 s. Enzyme activity was calculated based on the change in

absorbance over time, using the molar extinction coefficient (ε) of 26.6 M^{-1} cm^{-1}, and the results were expressed in nmol/min/µg of protein.

2.3.4. Superoxide dismutase (SOD) activity

Superoxide dismutase (SOD) activity was determined using a reaction mixture containing 100 µL of enzymatic extract, 130 mM methionine, 2 mM nitroblue tetrazolium (NBT), and 200 µM riboflavin, prepared in 50 mM potassium phosphate buffer (pH 7.0). The reactions were exposed to an 80 W fluorescent lamp for 15 min to induce the photochemical response. In parallel, identical reactions were conducted in the dark as negative controls. Sample absorbance was measured at 560 nm, and SOD activity was calculated using the molar extinction coefficient (ε) of 14.1 M^{-1} cm^{-1}, with results expressed in nmol/min/µg of protein.

2.4. Statistical analysis

All data obtained from the quantification of photosynthetic pigment levels and enzyme activities measured before application and at seven and 14 days after application were analyzed using Analysis of Variance (ANOVA). Mean comparisons were performed using the Scott-Knott test at a 5% significance level. Additionally, the difference between the initial and final values of photosynthetic pigments (ΔChl) and enzyme activity (ΔCAT, ΔSOD, and ΔPOX) across the three time points was calculated to assess the true effect of the treatment. The formula used was Δ = (value before application)/1 + (value seven days after application)/7 + (value 14 days after application)/14. This approach allows for a more accurate assessment of treatment effects and prevents isolated differences at specific time points from being misinterpreted. The calculated values were also analyzed using ANOVA, with mean comparisons conducted using the Scott-Knott test at a 5% significance level. All statistical analyses were performed using Sisvar software (version 5.6).

3. Results and discussion

3.1. Levels of photosynthetic pigments and leaf green area

Overall, a significant increase in total chlorophyll content was observed in treated plants (198.80 µg/g) compared to control plants (167.04 µg/g), as shown in **Table 1**. This increase was evident on both the 7th and 14th days after application, with a 48% (225.88 µg/g) increase on day 7 and a 38% (210.67 µg/g) increase on day 14 relative to pre-application levels (152.51 µg/g) (**Table 2**). Carotenoid levels were also higher in the treated plants, with 95 µg/g before application, reaching 117 µg/g on day 7 and 47 µg/g on day 14. In contrast, the control plants showed 80 µg/g, 96 µg/g, and 69 µg/g before application and on days 7 and 14, respectively (**Table 2**). Over time, treated plants exhibited a 16% higher carotenoid content (115.13 µg/g) compared to control plants (98.68 µg/g), as shown in **Table 1**.

Table 1. Photosynthetic pigment levels in treated and untreated mung bean plants (*Vigna radiata* L.) grown under greenhouse conditions. Results of ΔChl (chlorophyll) over the treatment period (before application, and seven and fourteen days after foliar application). Foliar application at a dose of 0.4 L ha^{-1}.

Treatment	Chlt	Chla	Chlb	Carotenoids
Control plants	167.04 µg/g^{b}	62.98 µg/g^{b}	104.06 µg/g^{b}	98.68 µg/g^{b}
Treated plants	198.80 µg/g^{a}	68.68 µg/g^{a}	130.12 µg/g^{a}	115.13 µg/g^{a}

Notes: Treatment means followed by the same letters do not differ statistically according to Analysis of Variance (ANOVA) based on the Scott-Knott test ($p < 0.05$). Chlt: total chlorophyll; Chla: chlorophyll a; Chlb: chlorophyll b. µg/g: chlorophyll content per gram of plant tissue.

Table 2. Photosynthetic pigment levels (total chlorophyll, chlorophyll a, chlorophyll b, and carotenoids) in black mung bean (*Vigna radiata* L.) leaves before and after treatment (7 and 14 days). Foliar application at a dose of 0.4 L ha^{-1}.

Before foliar application				
Treatment	**Chlt**	**Chla**	**Chlb**	**Carotenoids**
Control plants	131.16 µg/g^{b}	48.77 µg/g^{b}	82.38 µg/g^{b}	80.23 µg/g^{b}
Treated plants	152.51 µg/g^{a}	53.48 µg/g^{a}	99.03 µg/g^{a}	95.26 µg/g^{a}
Seven days after foliar application				
Control plants	187.23 µg/g^{b}	76.81 µg/g^{b}	110.42 µg/g^{b}	96.82 µg/g^{b}
Treated plants	225.88 µg/g^{a}	88.51 µg/g^{a}	137.17 µg/g^{a}	117.05 µg/g^{a}
Fourteen days after foliar application				
Control plants	137.03 µg/g^{b}	48.48 µg/g^{a}	88.54 µg/g^{b}	69.23 µg/g^{a}
Treated plants	210.67 µg/g^{a}	38.34 µg/g^{b}	172.33 µg/g^{a}	47.22 µg/g^{b}

Notes: Treatment means followed by the same letters do not differ statistically according to Analysis of Variance (ANOVA) based on the Scott-Knott test ($p < 0.05$). Chlt: total chlorophyll; Chla: chlorophyll a; Chlb: chlorophyll b. µg/g: chlorophyll content per gram of plant tissue.

Figure 1 reveals another significant finding, showing the green areas for each treatment. The leaf area of the treated plants expanded on both assessment days (7 and 14 days), reaching 33% and 28%, respectively, in contrast to 27% and 24% observed in the control plants. This corresponds to an overall increase of approximately 18% in leaf green area in treated plants compared to control plants, considering both evaluation time points (7 and 14 days after application).

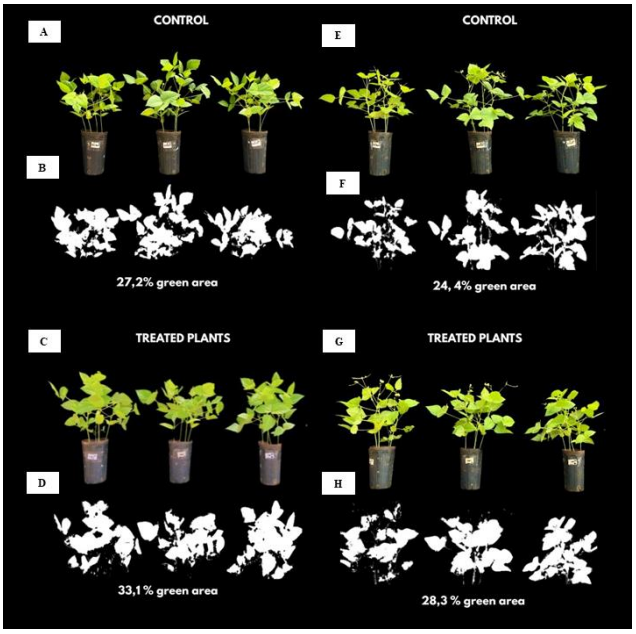

Figure 1. Growth of black mung bean plants (*Vigna radiata* L.) under greenhouse conditions. **(A,B)** Control plants and their leaf green area seven days after application. **(C,D)** Plants treated with Domínio® and their leaf green area seven days after application. **(E,F)** Control plants and their leaf green area fourteen days after application. **(G,H)** Plants treated with Domínio® and their leaf green area fourteen days after application.

3.2. Enzymatic activities

The results of the enzymatic activities are presented in **Table 3**, showing statistically significant effects for the three evaluated enzymes: catalase, peroxidase, and superoxide dismutase. A significant reduction in CAT activity was observed over time. Fourteen days after application, enzymatic activity decreased by approximately 67% (**Table 3**). Treated plants showed a 53% reduction from baseline to seven days after application and a 55% reduction from baseline to 14 days after application. Between the seventh and fourteenth days, activity remained relatively stable, with only a 4% variation during this period. In contrast, control plants (without organomineral application) exhibited a 27% increase in catalase activity over time (**Table 4**).

Table 3. Antioxidant enzyme levels in treated and untreated mung bean plants (*Vigna radiata* L.) grown under greenhouse conditions. Results of ΔCAT (catalase), ΔSOD (superoxide dismutase), and ΔPOX (peroxidase) over the treatment period (before application, and seven and fourteen days after foliar application). Foliar application at a dose of 0.4 L ha^{-1}.

Treatment	Catalase	Peroxidase	Superoxide dismutase
Control plants	6982 nmol/µg^{a}	9635 nmol/µg^{a}	10,403 nmol/µg^{a}
Treated plants	4180 nmol/µg^{b}	6656 nmol/mg^{b}	5546 nmol/µg^{b}

Notes: Treatment means followed by the same letters do not differ statistically according to Analysis of Variance (ANOVA) based on the Scott-Knott test ($p < 0.05$). nmol/min/µg of protein: nanomoles per minute per microgram of protein

Regarding peroxidase activity, significant differences were observed over the treatment period, with treated plants showing 30% lower enzymatic activity (6.656 nmol/µg) compared to control plants (9.635 nmol/µg) (**Table 3**). Although a 76% increase in SOD activity was recorded between the seventh and fourteenth days (**Table 4**), the overall variation during this period led to an approximately 87% decrease in enzymatic activity between the treated and untreated plants (**Table 3**). This reduction was primarily due to an eight-fold increase in enzymatic activity in control plants from the pre-application period to the fourteenth day (**Table 4**).

Table 4. Antioxidant enzyme activity (catalase, peroxidase, and superoxide dismutase) in black mung bean (*Vigna radiata* L.) leaves before and after treatment (7 and 14 days). Foliar application at a dose of 0.4 L ha^{-1}.

Before foliar application			
Treatment	**Catalase**	**Peroxidase**	**Superoxido dismutase**
Control plants	5889 nmol/µg^{a}	6373 nmol/µg^{a}	6373 nmol/µg^{a}
Treated plants	3812 nmol/µg^{b}	3812 nmol/µg^{b}	3812 nmol/µg^{b}
Seven days after foliar application			
Control plants	4150 nmol/µg^{a}	15,004 nmol/µg^{a}	2496 nmol/µg^{b}
Treated plants	1784 nmol/µg^{b}	11,851 nmol/µg^{b}	4085 nmol/µg^{a}
Fourteen days after foliar application			
Control plants	7503 nmol/µg^{a}	16,784 nmol/µg^{a}	50,788 nmol/µg^{a}
Treated plants	1709 nmol/µg^{b}	17,272 nmol/µg^{a}	17,272 nmol/µg^{b}

Notes: Treatment means followed by the same letters do not differ statistically according to Analysis of Variance (ANOVA) based on the Scott-Knott test ($p < 0.05$). nmol/min/µg of protein: nanomoles per minute per microgram of protein.

Additionally, the total protein levels were generally similar between the treated and control plants (**Table 5**). However, this finding may further support the positive biochemical responses of the organomineral-treated plants. If both groups maintained comparable protein levels, while only the control plants exhibited increased enzyme production (**Tables 3** and **4**), it suggests that treated plants allocate proteins to other essential metabolic pathways, thereby reducing the need to invest energy in stress protection.

Table 5. Total protein levels in black mung bean (*Vigna radiata* L.) leaves before and after treatment (7 and 14 days).

Treatment	**Before foliar application**	**7 days**	**14 days**
Control plants	7.29 mg/mL^{a}	7.20 mg/mL^{b}	13.01 mg/mL^{a}
Treated plants	7.54 mg/mL^{a}	9.23 mg/mL^{a}	11.98 mg/mL^{a}

Notes: Treatment means followed by the same letters do not differ statistically according to Analysis of Variance (ANOVA) based on the Scott-Knott test ($p < 0.05$).

4. Discussion

In this study, the results suggest that the foliar application of the organomineral Domínio® may promote some degree of stress tolerance in plants, as shown by the reduced activity of redox-related enzymes and the increased chlorophyll content in

treated plants compared to the controls (Section 3.1). These findings are in line with previous studies reporting the positive effects of foliar biostimulants on crop development [20–26]. For example, Selvam and Sivakumar [22] observed a 2% increase in chlorophyll a and b levels in *Vigna mungo* L. after the foliar application of plant- or algae-based extracts. Similarly, Verma et al. [26] reported increases in leaf number, leaf area, and photosynthetic pigments in *Vigna aconitifolia* following foliar spraying. These studies support our results, which show higher pigment content and green leaf area in Domínio®-treated plants (**Table 1**, **Figure 1**).

The increase in chlorophyll and leaf area directly impacts photosynthesis, which occurs in chloroplasts. Higher chlorophyll levels imply greater light absorption capacity, enhancing photosynthetic efficiency and potentially improving plant growth and productivity. However, photosynthesis naturally generates reactive oxygen species (ROS). During this process, oxygen can act as an electron acceptor in the photosystems, leading to ROS formation. Under normal conditions, these are neutralized by the plant's antioxidant system, involving enzymes like catalase, peroxidase, and superoxide dismutase [27].

When this system is underactivated, ROS can accumulate and disrupt cellular balance, leading to oxidative stress and potential damage [28,29]. Thus, the increased pigment levels and leaf area observed may indicate not only better photosynthesis but also a positive antioxidative response under the studied conditions, such as the temperature fluctuations (20 °C–35 °C) present during the experiment. This response may support plant health and help boost productivity.

The findings suggest that Domínio® may exert a beneficial influence on redox enzyme activity. Enzymatic activity in treated black mung bean plants was lower than in the controls (**Tables 3** and **4**), while photosynthetic pigments and green leaf area were significantly higher (**Tables 1** and **2**, **Figure 1**). The reduced enzymatic activity supports the idea that the organomineral acts through non-enzymatic mechanisms, allowing plants to use their resources more efficiently in essential metabolic processes. This strategy may be particularly beneficial for black mung bean, a crop sensitive to environmental stress.

The biostimulant's composition, rich in minerals and organic matter (N 1.30%, P_2O_5 3.0%, K_2O 2.0%, Mg 1.0%, B 0.5%, Mn 0.5%, Mo 0.1%, Zn 2.0%, and Total Organic Carbon 6.0%), may have helped neutralize ROS not through enzymatic activation but by creating a favorable nutritional environment for maintaining cellular balance. This mitigation likely involves non-enzymatic compounds such as amino acids, flavonoids, and carotenoids, or enzymatic action involving catalase, peroxidase, and superoxide dismutase, as noted by Gill and Tuteja [29].

Another key result was the 14% increase in carotenoid levels in treated plants (**Table 1**). Carotenoids help protect the photosystems from oxygen damage, act as antioxidants, and stabilize the proteins and membranes involved in light capture [30]. They play multiple roles in plant metabolism, including oxidative stress tolerance [29]. These results reinforce that Domínio® improved the biochemical profile of black mung bean plants, especially by increasing pigment levels and green leaf area. Thus, the application of this biostimulant represents an effective strategy in agricultural management, enhancing crop productivity. Substantial evidence demonstrates that

biostimulants based on *A. nodosum* and other macroalgae induce physiological and metabolic responses that result in significant field-level improvements [13,31–34].

5. Conclusion

The results of this study underscore the significant potential of organomineral treatments to modulate the biochemical responses of black mung bean (*V. radiata*) plants. Foliar application of Domínio® at a dose of 0.4 L ha^{-1} resulted in a notable 20% increase in total chlorophyll content and an expanded leaf green area, reflecting improved photosynthetic efficiency. Furthermore, the redox enzymatic system in treated plants exhibited lower activity compared to untreated controls. Considering the higher levels of photosynthetic pigments observed in treated plants, antioxidant activity may be primarily attributed to non-enzymatic mechanisms, such as carotenoids, which were also elevated relative to controls. Thus, in this study, we simulated field application conditions by adopting both the dosage of the product in the spray solution and the timing of application typically used in agricultural practice. The application of Domínio® may have provided essential nutrients that enhanced carotenoid synthesis. These findings demonstrate the potential of the organomineral as a tool for the physiological management of agriculturally important crops, particularly black mung bean. By combining bioactive compounds such as algal extracts and amino acids with essential nutrients, this formulation represents a sustainable alternative to optimize plant biochemical responses. In this context, its adoption holds the potential to significantly improve agricultural productivity and crop resilience.

Author contributions: Conceptualization, CFC, LTVM, CACdS, GFSF and WMM; methodology, CFC and JAdSO; data curation and analysis, CFC and JAdSO; writing—original draft, CFC and JAdSO; writing—review and editing, CFC, LTVM, NJMC, CACdS, WMM and JAdSO; funding acquisition and supervision, LTVM, CACdS, NJMC, GFSF, WMM and JAdSO. All authors have read and agreed to the published version of the manuscript.

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