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Effect of instantaneous light intensity after magnesium suppression in tomato and bell pepper cultivation

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ABSTRACT

Plants dynamically respond to varying light intensities, which may further interact with their nutrient status to affect gas exchange parameters. This study investigated the combined effect of instantaneous light intensity and magnesium suppression on tomato and bell pepper cultivation. Two independent experiments were conducted in September 2022 using the tomato variety Mariana (Sakata®) and bell pepper variety Magali R (Sakata®) at the Faculty of Agricultural and Technological Sciences, Dracena, São Paulo, Brazil. A completely randomized 2x5 factorial design was employed, with the first factor being the presence/absence of magnesium in the nutrient solution and the second factor being four light intensities: 0 (control), 600, 1200, and 1800 µmol m^{-2} s^{-1} photosynthetically active radiation (PAR) applied instantaneously using an IRGA device. Magnesium deficiency was confirmed to be a limiting factor for gas exchange responses in both tomato and pepper crops. Notably, the light intensity of 1200 µmol m^{-2} s^{-1} PAR elicited the most optimal gas exchange performance in both plant species.

Keywords: *Solanum lycopersicum* L., *Capsicum annuum* L., Plant nutrition, Gas exchange, Photosynthesis.

Efeito da intensidade luminosa instantânea após supressão do magnésio no cultivo do tomate e pimentão

RESUMO

As plantas apresentam respostas instantâneas quando expostas as diferentes intensidades de luz, e podendo mostrar respostas diferentes quando cultivadas com a restrição de magnésio nos parâmetros de trocas gasosas. O objetivo deste trabalho foi avaliar o efeito da intensidade luminosa instantânea após supressão do magnésio no cultivo do tomate e pimentão. Foram realizados dois experimentos independentes com as culturas do tomate variedade Mariana (Sakata®) e pimentão variedade Magali R (Sakata®) em Setembro de 2022, na Faculdade de Ciências Agrárias e Tecnológicas, localizada no município de Dracena estado de São Paulo. O delineamento experimental foi inteiramente casualizado (DIC) em esquema fatorial duplo 2x5 onde o primeiro fator foi composto com a presença e ausência de Magnésio em solução nutritiva, interagindo com quatro intensidades luminosas, sendo elas: zero (controle); 600; 1200 e 1800 µmol $m^{-2}s^{-1}$ de radiação fotossinteticamente ativa (PAR), fornecida de maneira instantânea com o uso do aparelho IRGA. O magnésio é um fator limitante nas respostas de trocas gasosas nas culturas do tomateiro e pimentão. A intensidade luminosa de 1200 µmol m^{-2} s^{-1} de radiação fotossinteticamente ativa (PAR) apresentou melhor resposta nas trocas gasosas nas culturas do tomateiro e pimentão.

Palavras-chave: *Solanum lycopersicum* L., *Capsicum annuum* L, Nutrição vegetal, Trocas gasosas, Fotossíntese.

1. Introduction

Tomato (*Solanum lycopersicum* L.) and bell pepper (*Capsicum annuum* L.) crops require special attention when it comes to their nutrition. Deficiency of certain elements can have a detrimental impact on the initial stages of plant development. Among these elements, magnesium (Mg^{2+}) is particularly important as it plays a crucial role in various developmental processes. It is an integral part of the chlorophyll molecule, facilitating carbon dioxide (CO_2) assimilation, and serves as a cofactor for enzymes. Additionally, it forms a structural component of the ribosome (Bakshi and Gilroy, 2022).

Furthermore, magnesium is essential for chlorophyll synthesis and acts as an activator of the carboxylation of ribulose 1,5 bisphosphate (RuBP) by forming a complex with the carbamate group and RuBP activase. When magnesium is deficient, plants can exhibit symptoms of chlorosis, characterized by yellowing of the leaves between the veins, and a decrease in yield due to reduced carbohydrate transport from source to sink tissues (Faiz et al., 2021; Lisboa et al., 2021).

In field cultivation, plants are exposed to various climatic variations, with light intensity and quality being particularly influential on instantaneous photosynthesis, germination, and flowering induction. To optimize growing conditions, controlled environments are necessary, allowing for precise control over light quality and intensity through artificial means. Light-emitting diodes (LEDs) have emerged as a valuable tool in this regard, offering the ability to regulate both light intensity and spectrum while significantly reducing energy consumption. The precise control of LED spectra can also promote the accumulation of important plant metabolites (Tarakanov et al., 2022).

Photosynthesis is a crucial process for plant growth, where light energy is converted into chemical energy. Plants capture CO_2 from the environment and release oxygen into the atmosphere during this process. Understanding the light saturation points in vegetables is essential to maximize production yields. Light detection in plants involves specialized molecules called photoreceptors, consisting of a protein linked to a pigment called chromophore, which absorbs photons. Morphologically, light restriction can impact plant growth from the early stages, causing etiolation and making seedlings more fragile during transport and planting (Kochetova et al., 2022).

Conversely, excess light can also damage plant structures, affecting photosynthesis and carbon dioxide uptake. Inadequate ventilation and exhaust can lead to a CO_2 deficiency in crops, hampering development and maturation. Therefore, maintaining a balanced light environment is crucial to minimize damage (Lazar et al., 2022).

Overall, light intensity and relative air humidity have both positive and negative effects on plant rooting and nutrient production. Research results have suggested that achieving a balance between light intensity and relative humidity is beneficial for both rooting and overall plant development (Ding et al., 2022). In light of the above, this study aimed to assess the effect of instantaneous light intensity following magnesium suppression on the cultivation of tomatoes and bell peppers.

2. Material and Methods

Two separate experiments were conducted in September 2022 using the Mariana tomato variety (Sakata®) and the Magali R pepper variety (Sakata®). These experiments took place at the Faculty of Agricultural and Technological Sciences, situated in the municipality of Dracena, São Paulo State, Brazil. The experimental design was completely randomized (CRD) in a 2x5 double factorial scheme. The first factor consisted of the presence or absence of magnesium in the nutrient solution, interacting with four levels of light intensity: 0 (control), 600, 1200, and 1800 µmol m^{-2} s^{-1} of photosynthetically active radiation (PAR).

The seedlings were approximately 8.52 cm in size and had 5±1 leaves at transplantation. They were cultivated in 5.0 L capacity pots filled with nutrient solution, with nutrient concentrations adapted from Lisboa et al., (2021). Nutrient solution composition included: 0.75 g L^{-1} of $Ca(NO_3)_2$; 0.53 g L^{-1} of KCl; 0.15 g L^{-1} of P_2O_5 + Ca; 0.4 g L^{-1} of $MgSO_4$; 1.5×10^{-2} g L^{-1} of $CuSO_4$; 2.0×10^{-2} g L^{-1} of $ZnSO_4$; 1.5×10^{-1} g L^{-1} of $MnSO_4$; 1.5×10^{-1} g L^{-1} of H_3BO_3; 1.5×10^{-2} g L^{-1} of Na_2MoO_4; and 3.0 g L^{-1} of EDTA+Fe(6%). Electrical conductivity was adjusted daily to 2,000 µS, and the pH was maintained at 6.4±2.

After 30 days of cultivation in the nutrient solution, tomato and pepper plants were subjected to five levels of instantaneous light intensity, as described earlier, provided by light-emitting diode (LED) lamps. A portable gas exchange device, specifically the Infra-Red Gas Analyzer (IRGA) by ADC BioScientific Ltd (model LC-Pro), was employed to determine various parameters, including the rate of CO_2 assimilation (A – µmol CO_2 m^{-2} s^{-1}), transpiration (E – mmol H_2O m^{-2} s^{-1}), stomatal conductance (gs – mol H_2O m^{-2} s^{-1}), and internal concentration of CO_2 in the substomatal chamber (ci – µmol mol^{-1}), with a constant CO_2 level of 380 ppm. To calculate water use efficiency (WUE), the following formula was applied:

$$WUE = \frac{A}{E}$$

Statistical analysis involved a series of steps. Firstly, normality tests using the Shapiro-Wilk test were conducted to ensure the data met the required assumptions. After confirming normality, an analysis of variance (ANOVA) was performed using the F test ($p<0.05$) for the nutrient factors. The means of these factors were compared using Tukey's test at a 5% level of significance, following the method of Banzatto and Kronka (2013).

For the light intensity factor, regression analysis was employed, evaluating linear, quadratic, and cubic models. The significance and coefficient of determination (R^2) were considered in model selection. Additionally, a Pearson correlation analysis was conducted. Furthermore, a principal component analysis (PCA) was carried out, following the procedures outlined in Galindo et al., (2022), utilizing the statistical software R (R Core Team, 2015).

3. Results and Discussion

In the tomato crop, there was an interaction between the factors for the rate of CO_2 assimilation (A). When cultivated with all nutrients and at a maximum light intensity of 1,303.83 µmol m^{-2} s^{-1} of photosynthetically active radiation (PAR), a positive linear response to increased light intensity was observed (Table 1). It is important to note that the suppression of magnesium led to a reduction of approximately 59.27% in comparison to plants grown with all nutrients.

Similarly, the A of pepper plants showed a negative response to magnesium restriction, which was approximately 72% lower than in plants receiving all nutrients. Both nutritional conditions, with all nutrients and in the absence of magnesium, exhibited quadratic responses, with maximum points at 1,272.00 and 1,180.00 µmol m^{-2} s^{-1} of PAR, respectively (Table 2).

Table 1. Instantaneous mean values and regressions of the CO_2 assimilation rate (A – µmol CO_2 m^{-2} s^{-1}); transpiration (E – mmol H_2O m^{-2} s^{-1}); stomatal conductance (gs – mol H_2O m^{-2} s^{-1}), internal CO_2 concentration in the substomatal chamber (ci – µmol mol^{-1}) and water use efficiency (WUE) of tomatoes grown with all nutrients and with the suppression of magnesium interacting with light intensities.

Nutrients (N)	A	E	gs	ci	WUE
All	10.24a	4.11a	0.262a	304.41b	2.37a
-Mg	4.17b	1.79b	0.085b	337.70a	2.70a
MSD	1.93	0.20	0.015	27.15	0.78
p-value	0.0001**	0.0001**	0.0001**	0.0175*	0.3991ns
Light (L)					
0	-2.90c	2.93b	0.147b	435.33a	-1.10c
600	8.02b	2.91bc	0.171b	309.16b	2.79b
1200	10.45ab	2.52c	0.215a	296.58b	4.23a
1800	13.25a	3.45a	0.160b	243.16c	4.23a
MSD	3.63	0.39	0.029	50.92	1.46
p-value	0.0001**	0.0001**	0.0001**	0.0001**	0.0001**
p-value NxL	0.0006**	0.0001**	0.0001**	0.2063ns	0.0483**
CV%	46.08	12.10	15.56	14.49	52.72
GA	7.20	2.95	0.173	321.06	2.53

	Nutrient	Regression	R^2	p-value
A	All	$y= -2.22 + 0.02991x - 0.00001147x^2$	0.8281	0.0001**
	-Mg	$y= -2.75 + 0.00770x$	0.7394	0.0001**
E	All	$y= 3.63 + 0.00053x$	0.5326	0.0001**
	-Mg	$y= 2.40 - 0.00254x + 0.00000133x^2$	0.5847	0.0001**
gs	All	$y= 0.19 + 0.00021x - 0.00000010x^2$	0.5216	0.0001**
	-Mg	---	---	0.5264Ns
ci	All	$y= 401.98 - 0.20919x + 0.000071x^2$	0.6776	0.0058**
	-Mg	$y= 442.78 - 0.11675x$	0.6991	0.0001**
WUE	All	$y= -0.70 + 0.00792x - 0.00000322x^2$	0.8025	0.0001**
	-Mg	$y= -1.41 + 0.0076x - 0.0000022x^2$	0.7543	0.0253*

GA: General average; CV: Coefficient of variation; MSD: Minimum Significant Difference. ** - significant at the 1% probability level ($p<0.01$); * - significant at the 5% probability level ($0.01=<p<0.05$). Means followed by the same letter do not differ statistically. The Tukey test was applied at the level of 5% probability of the event occurring; (-Mg): magnesium suppression

Tabela 2: Instantaneous mean values and regressions of the CO_2 assimilation rate (A – μmol CO_2 m^{-2} s^{-1}); transpiration (E – mmol H_2O m^{-2} s^{-1}); stomatal conductance (gs – mol H_2O m^{-2} s^{-1}), internal CO_2 concentration in the substomatal chamber (ci – μmol mol^{-1}) and water use efficiency (WUE) of peppers grown with all nutrients and with the suppression of magnesium interacting with light intensities.

Nutrient (N)	A	E	gs	ci	WUE
All	11.11a	3.56a	0.226a	296.25a	3.02a
-Mg	3.11b	1.15b	0.054b	296.41a	2.82a
MSD	1.06	0.14	0.018	25.32	0.76
p-value	0.0001**	0.0001**	0.0001**	0.9895ns	0.5964ns
Light (L)					
0	-1.86d	2.12b	0.119b	417.50a	-0.94c
600	8.00c	2.51a	0.146ab	272.75b	3.10b
1200	12.30a	2.59a	0.162a	243.50b	5.25a
1800	10.00b	2.20b	0.133ab	251.58b	4.27ab
MSD	1.99	0.27	0.034	47.49	1.43
p-value	0.0001**	0.0001**	0.0131*	0.0001**	0.0001**
p-value NxL	0.0001**	0.0001**	0.2030ns	0.8804ns	0.0375*
CV%	25.60	10.62	22.67	14.64	44.87
GA	7.11	2.35	0.140	296.33	2.92

	Nutrient	Regression	R^2	p-value
A	All	$y= -2.38 + 0.03230x - 0.00001269x^2$	0.8908	0.0001**
	-Mg	$y= -1.51 + 0.01265x - 0.00000536x^2$	0.7978	0.0001**
E	All	$y= 3.04 + 0.00199x - 0.00000102x^2$	0.6204	0.0001**
	-Mg	---	---	0.1018Ns
gs	All	---	---	0.0952Ns
	-Mg	$y= 0.047 + 0.00004x - 0.00000003x^2$	0.6074	0.0001**
ci	All	$y= 417.88 - 0.28130x + 0.0001044x^2$	0.9196	0.0001**
	-Mg	$y= 409.30 - 0.27644x + 0.0001078x^2$	0.6151	0.0038**
WUE	All	$y= -0.84 + 0.00933x - 0.00000354x^2$	0.9453	0.0001**
	-Mg	$y= -1.34 + 0.01104x - 0.00000459x^2$	0.7245	0.0001**

GA: General average; CV: Coefficient of variation; MSD: Minimum Significant Difference. ** - significant at the 1% probability level ($p < 0.01$); * - significant at the 5% probability level ($0.01 =< p < 0.05$). Means followed by the same letter do not differ statistically. The Tukey test was applied at the level of 5% probability of the event occurring; (-Mg): magnesium suppression.

A significant negative Pearson correlation was observed between the A and the CO_2 concentration in the substomatal chamber (*ci*), indicating that as the *ci* increases, the rate of gas assimilation decreases. However, there was a positive correlation between the A and water use efficiency (WUE) (Figure 1).

When a plant is cultivated with magnesium restriction, the A is compromised due to the lower concentration of magnesium in the plant's internal tissues. This affects the growth of the aerial part of the plant (Pessoa et al., 2022). The critical range of magnesium in the dry weight of the leaf falls between 0.1% and 0.2% in various crops, including wheat, potato, rice, corn, sorghum, and barley. Although net CO_2 assimilation may be higher, it does not translate into increased plant biomass. This implies that the efficiency of converting carbon gas into sugars is compromised (Hauer-Jákli & Tränkner, 2019; Lazar et al., 2022).

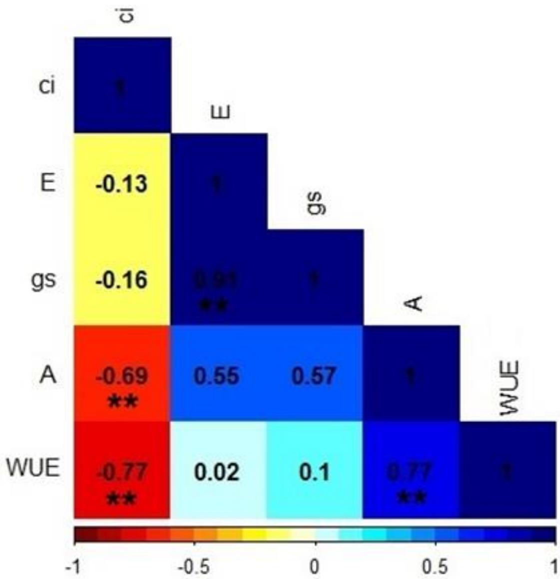

Figure 1. Significant Pearson correlations between gas exchange parameters of tomatoes (T) and peppers (P) grown with all nutrients (All) and with magnesium suppression (-Mg)

Light intensity is also a factor that influences carbon dioxide assimilation. *In vitro* studies have shown that changes in carbon fixation physiology can alter leaf anatomy, resulting in smaller leaves with reduced leaf blade thickness (Calazans Júnior et al., 2022). These effects can be exacerbated by magnesium restriction (Lisboa et al., 2021). As a result, instantaneous and CO_2-saturated photosynthesis, as well as the maximum rates of ribulose 1,5 bisphosphate (RuBP) and electron transport, are compromised when plants are grown with nutrient restrictions, such as potassium and magnesium deficiencies (Faiz et al., 2021). Additionally, chlorophyll fluorescence and electron transport decrease in both nutrient deficiencies, while dark respiration increases, indicating that plants require more energy to maintain their metabolic functions (Rogiers et al., 2020).

Studies by Faizan et al. (2022) suggested that foliar application of magnesium oxide nanoparticles (MgO-NPs) under conditions of arsenic stress in soybean plants can result in a 17% increase in height and a 15% increase in dry weight. This is attributed to the positive response of magnesium, which improved the net photosynthetic rate by 12.9%, stomatal conductance (g_s) by 13.4%, intercellular CO_2 concentration by 15.3%, and transpiration by 14.7%. Additionally, the efficiency of photosystem II (PSII) improved, leading to a more efficient response to oxidative stress with reduced hydrogen peroxide (H_2O_2) and lipid peroxidation in leaves. These findings support the key role of magnesium in photosynthetic parameters and its ability to enhance resistance to oxidative stress.

Instantaneous transpiration (E) was significantly reduced in tomato plants when magnesium was restricted, resulting in a decrease of approximately 56.44%. The minimum point for transpiration occurred at 954.88 μmol m^{-2} s^{-1} of PAR. In the absence of magnesium, transpiration decreased by approximately 67.55% compared to plants grown with all nutrients. On the other hand, the transpiration rate of pepper plants grown with all nutrients exhibited a quadratic response, with a maximum point at 1,050 μmol m^{-2} s^{-1} of PAR (Table 2). Magnesium restriction affected gas exchange parameters in both vegetable species (Figure 2).

Lack of light also negatively affected gas exchange parameters, as shown in Figure 3. There was no significant difference in g_s with varying light intensities in tomato plants when grown under magnesium restriction. In contrast, tomato plants with all nutrients exhibited a positive quadratic response, with a maximum light saturation point at 789.47 μmol m^{-2} s^{-1} of PAR, which was approximately 67.55% higher than under magnesium restriction (Table 1). In the case of pepper plants grown under magnesium restriction, there was a statistically significant difference in light intensity, and a quadratic response was observed with a maximum point at 666.66 μmol m^{-2} s^{-1} of PAR. The absence of magnesium resulted in a reduction of approximately 76.10% in g_s (Table 2).

Both E and g_s can be influenced by the nutrient concentrations within plant organs. In cucumbers, higher environmental CO_2 levels can promote root growth, but this increased root mass may not compensate for the reduced absorption rates of other nutrients such as nitrogen, potassium, calcium, and magnesium. Even when cultivated under low temperatures, the mass flow of nutrients can negatively affect the rate of transpiration (Li et al., 2023).

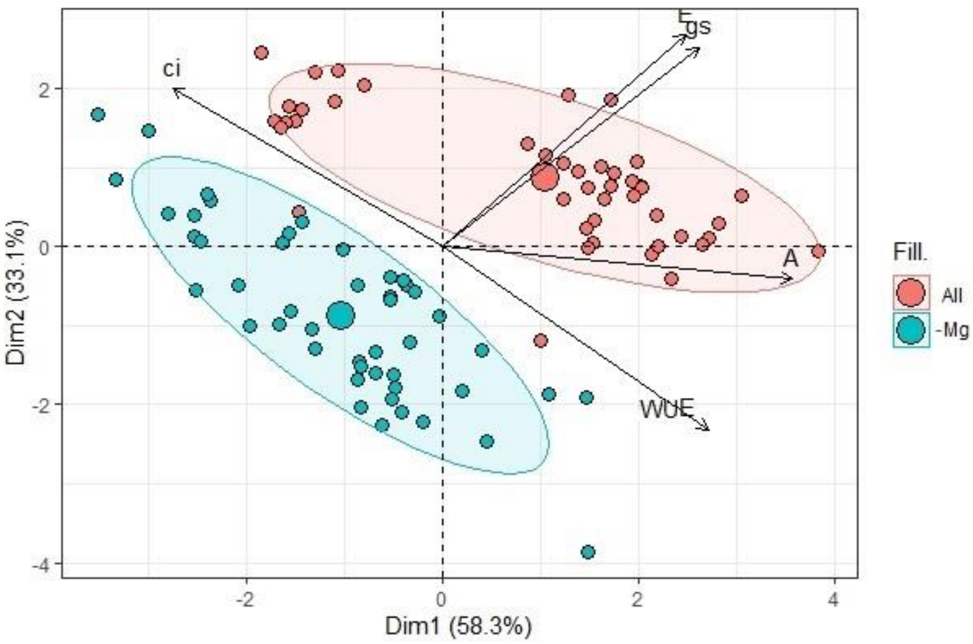

Figure 2. Biplot graph of the principal component analysis (PCA) of the inference of contribution of the crop with all nutrients and with magnesium restriction in crop the tomato and bell pepper.

Magnesium restriction led to higher *ci* in the tomato substomatal chamber, resulting in a 9.85% increase. The response was linear when magnesium was restricted, whereas, with all nutrients, a quadratic response was observed with a maximum light saturation point at 1,473.00 m^{-2} s^{-1} of PAR (Table 1). In the case of pepper plants, both with all nutrients and under magnesium restriction, a quadratic response was observed, with maximum light saturation points at 1,347.00 and 1,282.00 m^{-2} s^{-1} of PAR, respectively (Table 2).

Furthermore, balancing the partial supply of nitrate (NO^{3-}) can have a significant positive impact on various physiological parameters. It can notably enhance the net photosynthetic rate, transpiration rate, g_s, and *ci* in plants, particularly when they are facing water restrictions. Consequently, the provision of nitrogen can act as a mitigating factor, alleviating the adverse effects stemming from magnesium deficiency (Deng et al., 2023). Due to magnesium restriction, stomatal function may become compromised, leading to the closure of stomatal pores. This, in turn, results in a higher concentration of internal CO_2. Such a scenario could impede efficient gas exchange and compromise the rate of CO_2 fixation, as evidenced in Tables 1 and 2.

Moreover, Modarelli et al. (2022) demonstrated that increasing light intensity in lettuce cultivation can elicit a more favorable response in liquid photosynthesis. This ensures a more consistent electron transport rate and, additionally, stimulates the synthesis of anthocyanins and carotenoids. These findings have positive implications for plant protection, especially when plants are exposed to high-intensity light stress. Once again, tomatoes exhibited a quadratic response to WUE when grown with all nutrients and under magnesium restriction. The points of maximum light saturation were 1,229.81 and 1727.27 m^{-2} s^{-1} of PAR (Table 1). Similarly, pepper plants also demonstrated a quadratic response in terms of WUE. This was observed in plants grown with all nutrients and under magnesium restriction, with maximum light saturation points of 1,317.00 and 1,202.00 m^{-2} s^{-1} of PAR, respectively, as indicated in Table 2.

The stomatal apparatus can undergo alterations due to nutritional factors and even variations in light intensity, resulting in changes in stomatal size and density. Consequently, both the size and quantity of stomata can exhibit rapid responses when exposed to sudden changes in light levels. This phenomenon implies that plants with faster stomatal opening also experience quicker induction of photosynthesis, which leads to a greater accumulation of biomass.

However, it may also result in lower specific WUE when subjected to varying light intensities (Xiong et al., 2022). The ability to manipulate stomatal regulation, including adjustments in stomatal size and density, can serve as a viable strategy to enhance crop yield. Additionally, it may help mitigate some of the current challenges associated with climate change in agricultural environments (Sinha et al., 2022).

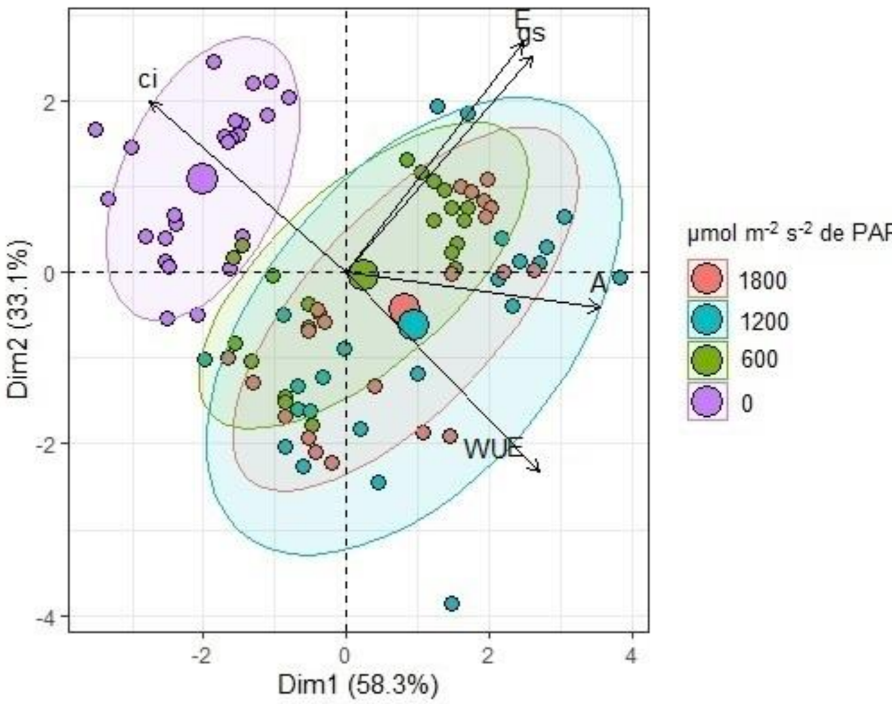

Figure 3. Biplot graph of principal component analysis (PCA) of the inference of contribution of instantaneous light intensities in tomato and pepper crops.

4. Conclusions

Magnesium serves as a key limiting factor in the gas exchange responses of tomato and pepper crops. A light intensity of 1200 µmol m^{-2} s^{-1} of photosynthetically active radiation promotes the most favorable gas exchange outcomes in both tomato and pepper cultures.

Authors' Contribution

The authors Lucas Aparecido Manzani Lisboa and José Carlos Cavichioli contributed to the planning and execution of the experiment, while Lucas Aparecido Manzani Lisboa, Paulo Alexandre Monteiro de Figueiredo, and Fernando Shintate Galindo were involved in data analysis, writing, and content translation.

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