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Particle Film Improves the Physiology and Productivity of Sweet Potato without Affecting Tuber's Physicochemical Parameters

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Abstract: In tropical areas, the lower productivity of sweet potato has been related to unfavorable climatic conditions, as heat stress caused by high temperatures limits the optimal genotypic expression of plants. Innovative techniques, such as particle films, have been proposed to reduce productivity loss caused by such conditions. Herein, we examine whether applying calcium oxide particle films could minimize heat stress on sweet potato under field conditions, reflecting higher productivity. For this purpose, sweet potato plants were exposed to four concentrations of calcium oxide particle film (0, 5, 10, and 15% w/v) applied onto leaves and assessed regarding the physiological, physicochemical, and productivity parameters. Overall, in plants treated with calcium oxide particle films, the photosynthetic rate, intercellular CO_2 concentration, water use efficiency, and carboxylation efficiency increased compared to untreated plants. Moreover, we observe a reduction in leaf temperature and stomatal conductance of up to 6.8% and 45%, respectively, in sweet potato plants treated with 10% w/v, resulting in higher productivity (34.97 ton ha^{-1}) compared to the control (21.55 ton ha-1). No effect is noted on tuber physicochemical parameters. In summary, the application of a calcium oxide particle film seems to favor sweet potato crops, alleviating the stress caused by hot climatic conditions in tropical regions.

Keywords: ecophysiology; yield gap; heat stress; bioclimatic conditions; food security

1. Introduction

The climate has a fundamental role in crop establishment due to its direct impact on the germination, growth, survival, and productivity of plants [1,2]. Accordingly, adverse conditions such as a high air temperature and light intensity impair plant development and, consequently, reduce their productivity [1,3]. Thus, cultural practices to mitigate these conditions are necessary to fill this yield gap and guarantee food security in developing countries [4].

Technologies such as particle films can alleviate the adverse climatic conditions during crop cultivation. These films contain aqueous formulations from inert mineral particles that protect the plant crop canopy from solar irradiance and mitigate the effects of high temperatures [5]. As a result, treated plants may exhibit an increased photosynthetic rate and water use efficiency, resulting in higher productivity and fruit quality [6]. Similar responses have been observed when treated plants were placed under heat and dry stresses [5,7], attributed to the artificial shading promoted by particle films [8–10]. Thus, the productivity of crops cultivated in tropical areas, characterized by relatively higher temperatures and solar radiation [11], can be potentially improved by applying particle films.

Sweet potato (*Ipomoea batatas* L.) is a crop cultivated in tropical and subtropical regions by traditional and modern agricultural systems, identified as one of the crops able to reduce food security risks [4,12]. This high value is associated with the crop's nutrient-rich composition, feasibility to grow three times a year, and tolerance to drought and excess rainfall [4]. However, changes in climate conditions such as high temperature and solar radiation can limit sweet potato productivity. Correspondingly, crop productivity tends to be higher in subtropical conditions than in tropical. For instance, in Mexico, the average productivity in 2019 was 19.12 tons per hectare, while in Brazil, it was 14.06 tons per hectare [13]. Thus, using technologies to mitigate adverse conditions experienced by sweet potato crops is necessary to guarantee their leading role in food security [14].

The application of particle films could be a means of alleviating the adverse effects of abiotic stress on sweet potato crops. Here, we test whether applying calcium oxide (CaO) improves the physiology of the sweet potato crop, resulting in a high tuber productivity and physicochemical quality. We predict that plants that receive CaO particle films improve in photosynthesis and crop productivity due to the particle films' artificial shading of leaves.

2. Materials and Methods

2.1. Study Area and Experimental Design

The study was carried out in an experimental area (Campus Rural–University Federal of Sergipe) at Sao Cristóvão, Sergipe, Brazil (10 55′27″ S, 37 12′01″ W, 46 m a.s.l.) from April to September 2018. We used the cultivar "Ourinho" and established the crop in four rows (18 m × 0.6 m; length × width each row) with 1 m spaces between them and 0.3 m among plants. Drip irrigation was applied based on the evapotranspiration values from a meteorological station, and fertilizers were used according to soil analysis performed before crop establishment (20 kg ha^{-1} of N; 90 kg ha^{-1} of P_2O_5; 90 kg ha^{-1} of K_2O) and agronomic recommendations (30 days after planting, 30 kg ha^{-1} of N, 40 kg ha^{-1} of P_2O_5 and 60 kg ha^{-1} of K_2O).

We monitored climatic conditions (mean air temperature, precipitation, and solar radiation) during the experiment using an automated station located 50 m away (Figure 1) and set up the investigation as a randomized block design (n = 4; each row as one block) with four treatments (control (0), 5, 10, and 15% w/v of CaO; Figure 2). We chose these CaO concentrations based on previous studies [10] and preliminary analysis.

The calcium oxide particle films (solubility at 25 °C: 0.12 g/100 mL; Isolab, São Paulo, Brazil) and water (control) were applied whenever the luminosity was reduced on leaves [10], showing a 20% reduction in the initial application. We used a digital colorimeter model CR 400 (Konica Minolta, Japan) to measure luminosity values on five leaves from the plant canopy (n = 4 plants per treatment/block). This colorimeter shows values on a scale from 0 (total light absorption) to 100 (total light reflection), associated with the reflective properties of leaves and CaO particle film residue. These values were compared with the control to identify the variation of luminosity related to film persistence or removal due to precipitation. In total, we applied eight sprays during the cultivation (30, 45, 60, 75, 90, 105, 120, and 133 days after planting) using an electric hand sprayer (model Kawashima PEM-P20) with a flow rate of 2.9 L min^{-1} and a pressure of 450 KPa.

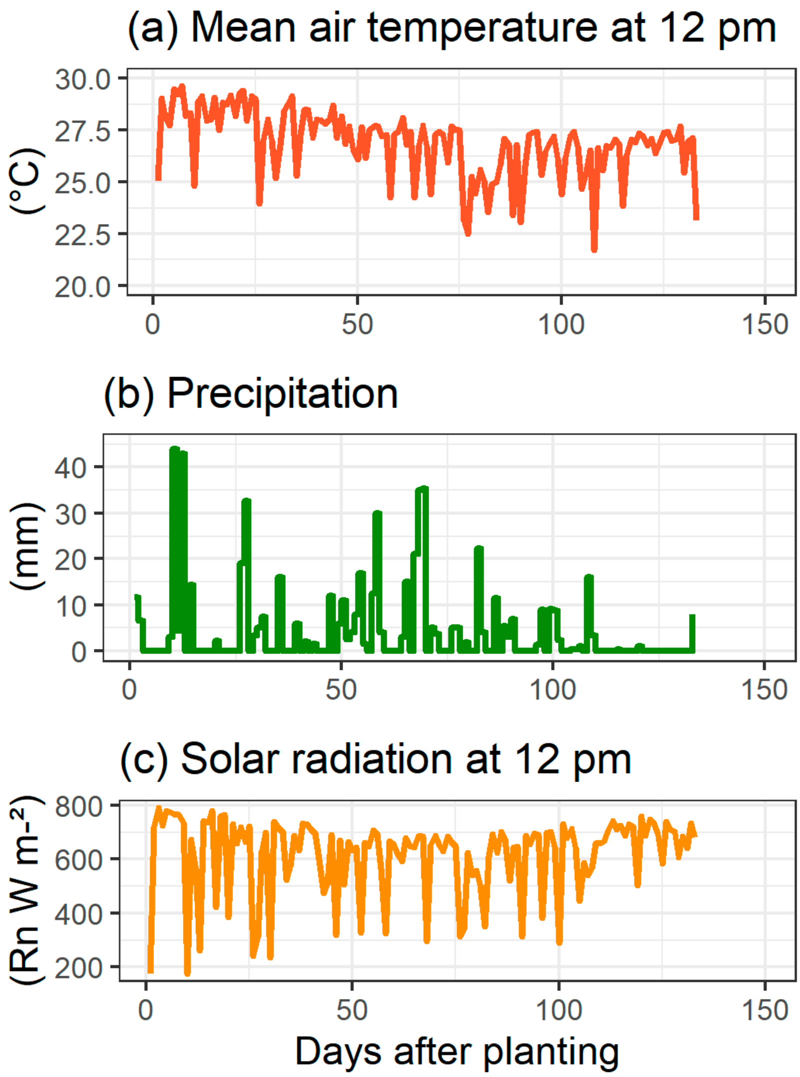

Figure 1. (**a**) Mean air temperature at 12 pm, (**b**) daily precipitation, and (**c**) solar radiation at 12 pm during the experimental period (days after planting) at São Cristóvão, Sergipe, Brazil. Data were acquired from an automated meteorological station 50 m away from the crops.

2.2. Gas Exchange

We evaluated gas exchange variables 30 days before harvesting at 9 am as follows: photosynthetic rate (µmol CO_2 m^{-2} s^{-1}), intercellular CO_2 content (µmol CO_2 mol air^{-1}), leaf temperature (°C), and stomatal conductance (mol H_2O m^{-2} s^{-1}). The parameters were measured using infrared gas exchange (IRGA, model LI-6400XT, Li-cor, Biosciences Inc., Lincoln County, NB, USA) calibrated according to the local climatic conditions (photosynthetically active solar radiation 1500 µmol m^{-2} s^{-1}) and CO_2 reference concentration of 400 ± 2 µmol mol^{-1}. The measurements were performed on expanded leaves (i.e., active leaves) without injuries in the middle of the plant canopy. Instantaneous water use efficiency (mol CO_2 (mmol H_2O)$^{-1}$) as photosynthetic rate/transpiration, intrinsic water use efficiency (mol CO_2 (mol H_2O)$^{-1}$) as photosynthetic rate/stomatal conductance, and instantaneous carboxylation efficiency (mol m^{-2} s^{-1}) as photosynthetic rate/intercellular CO_2 concentration were then calculated.

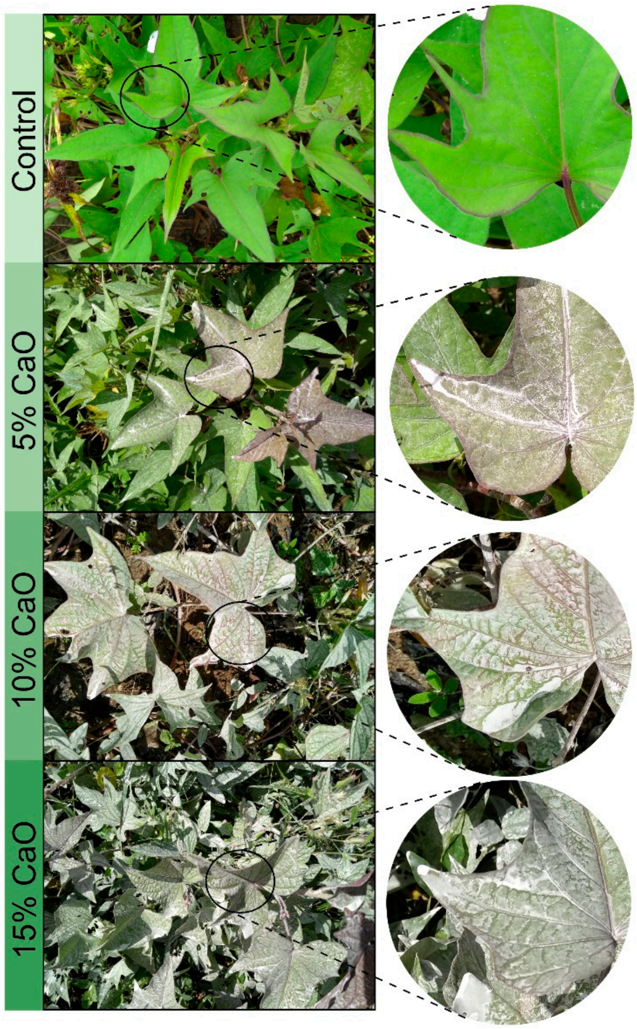

Figure 2. Leaves of sweet potato plants (*Ipomoea batatas* L.) after applying calcium oxide (CaO) particle films at 5, 10, and 15% w/v and control (water).

2.3. Physiological and Biochemical Parameters

We verified whether treatments could improve tuberous physicochemical variables and productivity. Thus, we measured color, firmness, total soluble solids, pH, titratable acidity, starch, and calcium content. Lastly, we measured tuberous productivity, number, and weight using a semi-precision balance (model Bel S2202H, São Paulo, Brazil) and then estimated as tons per hectare.

Four tubers per treatment from each block were used to perform the physicochemical analyses. We washed roots using water and sodium hypochlorite solution (100 mg L^{-1}) for five minutes and then placed them in a plastic tray. We measured color with a CR-400 colorimeter (model Chroma Meter, Konica Minolta, Osaka, Japan) in three parts of the highest diameter of the tuber region. We measured luminosity, red intensity, blue/yellow coordinate, hue angle, and chroma. The tuberous firmness was evaluated with a digital penetrometer (TR Turoni, 53205 model, Forli, Italy) in the same region where the color was measured, with three evaluations per replicate (measured in Newton—N).

We determined total soluble solids (^{0}Brix) by mashing roots and then used a digital refractometer (RTD-45 model, Instrutherm, São Paulo, Brazil). The mashed roots were also used to measure pH using a pH meter (model pHS-3E, LabMeter, São Paulo, Brazil) and titratable acidity by titration method with NaOH solution (0.01 N) according to [15], noting results as % citric acid (g 100 g^{-1}).

The content of starch was determined by the Lane–Eynon method. This method is based on reducing alkaline copper (Fehling) to cuprous oxide, with a final point indicated by methylene blue, which is reduced by the excess of reducing sugar levels [15,16]. Calcium content was determined by the permanganometric method described by [17], using an aliquot of 500 g of the tuberous.

2.4. Statistical Analyses

Data normality (residuals) and homogeneity of variances were checked by Shapiro–Wilk and Bartlett tests. We performed analyses of variance (ANOVA, $\alpha = 0.05$) to detect differences among treatments for gas exchange, physiological and biochemical, and productivity variables. We included blocks to account for their variance on treatment effects (y~x + error (block)) and the mean value of the replicates inside each treatment/block to avoid pseudoreplication insertion. When we found differences among treatments, the Tukey test was applied to compare means ($\alpha = 0.05$). We used agricolae [18] package to perform these analyses and designed graphics using ggplot2 [19] and esquisse [20] in R version 4.0.4 [21] and Corel Painter (Essential 7, Ottawa, ON, Canada).

3. Results

3.1. Gas Exchange

Given the previous reports that particle films affected the gas exchange of plants, we decided to investigate if the same could be observed in sweet potatoes. We found a reduction in stomatal conductance ($F = 61.11$; $df = 3, 9$; $p < 0.0001$) in all treatments compared to the control, and for plants with CaO 10% *w*/*v*, it represented a reduction of 45.6% (Figure 3a). The photosynthetic rate reduced ($F = 28.07$; $df = 3, 9$; $p < 0.0001$) in plants treated with CaO 15% *w*/*v*, while this rate was similar among the control and CaO at 5 and 10% *w*/*v* (Figure 3b).

We noted that the intercellular CO_2 concentration increased in plants treated with CaO particle films ($F = 1078$; $df = 3, 9$; $p < 0.0001$), mainly at 10% *w*/*v* (Figure 3c). However, the highest carboxylation efficiency ($F = 15.87$; $df = 3, 9$; $p < 0.0001$) was observed in control plants and those treated with CaO 5% *w*/*v* (Figure 3d). The leaf temperature ($F = 5.21$; $df = 3, 9$; $p = 0.023$) reduced by 0.8 °C (mean (control 31.22 °C)) in plants treated with CaO at 10 (30.37 °C) (Figure 3e).

We noted the highest instantaneous water use efficiency ($F = 74.21$; $df = 3, 9$; $p < 0.0001$) at CaO 15% *w*/*v* (Figure 4a). Conversely, sweet potato plants displayed an improvement in the intrinsic water use efficiency ($F = 37.32$; $df = 3, 9$; $p < 0.0001$) at CaO 5% and 10% *w*/*v* (Figure 4b).

3.2. Physicochemical and Productivity of Tuberous

We found that plants treated with calcium particle films did not present differences regarding tuber physicochemical variables, which included: color (blue/yellow coordinate ($F = 1.79$; $df = 3, 9$; $p = 0.21$), chroma ($F = 0.67$; $df = 3, 9$; $p = 0.58$), hue angle ($F = 1.97$; $df = 3, 9$; $p = 0.19$), luminosity ($F = 2.03$; $df = 3, 9$; $p = 0.18$), red intensity ($F = 2.30$; $df = 3, 9$; $p = 0.15$) (Figure S1, Supplemental Materials), calcium content ($F = 74.21$; $df = 3, 9$; $p < 0.0001$), firmness ($F = 0.92$; $df = 3, 9$; $p = 0.47$), pH ($F = 1.09$; $df = 3, 9$; $p = 0.40$), starch content ($F = 2.42$; $df = 3, 9$; $p = 0.29$), titratable acidity ($F = 1.11$; $df = 3, 9$; $p = 0.39$), and total soluble solids ($F = 1.09$; $df = 3, 9$; $p = 0.41$); (Figure S2, Supplemental Materials).

Conversely, sweet potato plants that received particle films at CaO 10 and 15% *w*/*v* increased tuberous productivity ($F = 22.08$; $df = 3, 9$; $p = 0.0001$) by 34.97 and 30.79 ton ha^{-1} in relation to the control (21.55 ton ha^{-1}), respectively (Figure 5).

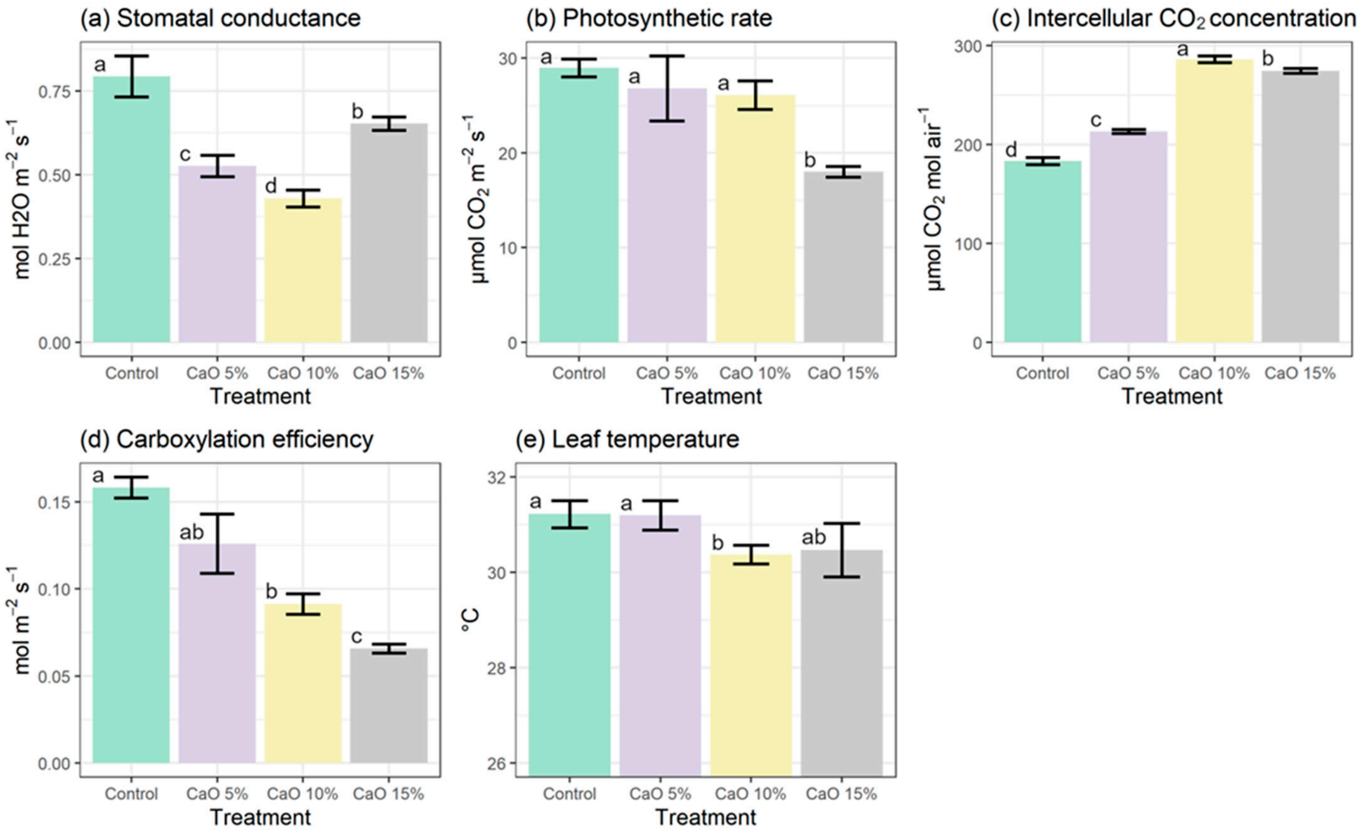

Figure 3. (**a**) Stomatal conductance (F = 61.11; df = 3, 9; $p < 0.0001$), (**b**) photosynthetic rate (F = 28.07; df = 3, 9; $p < 0.0001$), (**c**) intercellular CO_2 concentration (F = 1078; df = 3, 9; $p < 0.0001$), (**d**) carboxylation efficiency (F = 15.87; df = 3, 9; $p < 0.0001$), and (**e**) leaf temperature (F = 5.21; df = 3, 9; p = 0.023) of sweet potato (*Ipomoea batatas* L.) plants sprayed with calcium oxide (CaO) particle films at 5, 10, and 15% w/v and control (water). We performed measurements 30 days before harvesting using expanded leaves in the middle of the plant canopy. Values represent mean (±standard deviation), and bars followed by the same letter did not differ according to the Tukey test ($p < 0.05$). (n = 4).

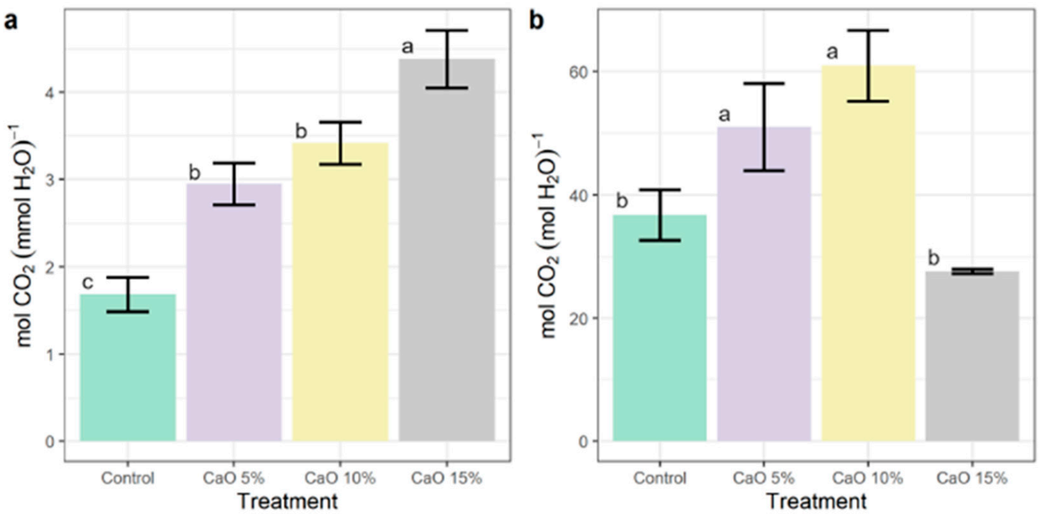

Figure 4. (**a**) Instantaneous water use efficiency (F = 74.21; df = 3, 9; $p < 0.0001$) and (**b**) intrinsic water use efficiency (F = 37.32; df = 3, 9; $p < 0.0001$) of sweet potato (*Ipomoea batatas* L.) plants sprayed with calcium oxide (CaO) particle films at 5, 10, and 15% w/v and control (water). Values represent mean (±standard deviation), and bars followed by the same letter did not differ according to the Tukey test ($p < 0.05$) (n = 4).

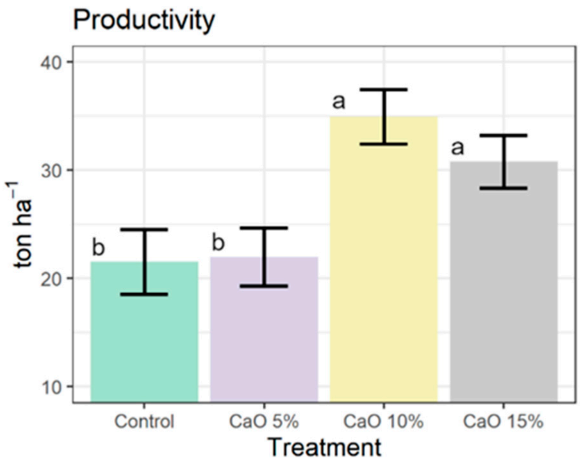

Figure 5. Tuberous root productivity of sweet potato (*Ipomoea batatas* L.) plants sprayed with calcium oxide particle films at 5, 10, and 15% *w*/*v* and control (water). Values represent mean (±standard deviation), and bars followed by the same letter did not differ according to the Tukey test ($p < 0.05$).

4. Discussion

Climatic conditions reduce plant productivity through effects on its physiology, affecting processes such as photosynthesis. We found that sweet potato plants with calcium oxide particles improved their physiology, increasing tuberous productivity, mostly at 10% *w*/*v*, without affecting tubers' physicochemical parameters. Our work demonstrated the use of particle films to mitigate the impact of warm conditions on sweet potato crops.

The CaO particle films seemed to protect sweet potato plants during conditions such as high temperature, maintaining their photosynthetic rate despite reducing stomatal conductance. For instance, control plants presented higher stomatal conductance and, in contrast, the photosynthetic rate remained similar for all CaO treatments, except at 15% *w*/*v*. This result indicated an improvement in light absorption and distribution in CaO-treated sweet potato plants, reflecting visible and ultraviolet radiation, which reduced the leaves' thermal tension and possibly radiation stress [22–24].

Interestingly, our results were also associated with leaf temperature reduction and stomatal conductance, decreasing the CO_2 influx into the sub-stomatal chamber and intercellular spaces due to an increased photosynthetic rate and carbon concentration values. Accordingly, a drop in stomatal conductance was more associated with reducing the leaf temperature and cooling transpiration mechanism than effects on stomatal movements [25]. Thus, the application of calcium oxide films minimized the impact of thermal stress on sweet potato plants, as reported in apple [26], coffee [10], and grape crops [27,28].

We observed a decrease in carboxylation efficiency at CaO 10% *w*/*v*, accompanied by a high internal CO_2 concentration and a reduction in stomatal conductance (Figure 3a,c,d, respectively). Carboxylation efficiency depends on the availability of CO_2 in the leaf mesophyll, light quantity, temperature, and rubisco activity [29]. The decrease in the instantaneous carboxylation efficiency at CaO 10% could be due to the increased light scattering owed to the CaO film, reducing light penetration to the mesophyll [30,31].

The application of calcium oxide particle films improved plants water use efficiency by modifying the trade-off between photosynthesis and transpiration. Both treatments that received CaO at 10 and 15% *w*/*v* improved their physiological variables, as indicated by intrinsic and instantaneous water use efficiency values. However, at 15% *w*/*v*, the former was lower than 10% *w*/*v*. This was probably due to a light limitation of photosynthesis due to shading and increased stomatal conductance, probably due to milder light and thermal stress [32,33].

In all treatments except CaO 15%, both water use efficiency parameters showed a considerable increase owing to the maintenance of a similar photosynthetic rate as the control, while reducing and optimizing stomatal conductance to avoid excess water losses.

This may be associated with leaf temperature reduction as well as the reflectance of excess solar radiation since sweet potato is a C3 plant and moderate light energy is enough to saturate photosynthesis [34,35]. Hence, we suggest that the 'water-saving effect' observed in sweet potato plants by applying calcium films can be sustainable for crop cultivation in regions with higher temperatures and solar radiation [34].

The particle films did not affect the physicochemical parameters of the tuber. Our results showed a continuous effect after calcium film application onto sweet potato plants. For instance, the same photosynthetic rates and a lower leaf temperature resulted in increased intercellular carbon and a better efficiency of the carboxylation process and water use efficiency. The condition proportioned after calcium application reduced radiation and thermal stresses without affecting physicochemical parameters [36,37].

5. Conclusions

Calcium particle films improve sweet potato plants' physiology and tubers' productivity without affecting their physicochemical parameters, mainly at 10% w/v. Further studies could assess the effects of calcium particle films on sweet potato plants submitted to drought conditions. Considering the importance of sustainable technologies for crop protection, studies such as ours may help to promote food security under future climate change scenarios.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12040558/s1, Figure S1: color adimensional values of blue/yellow coordinate, chroma, hue angle, luminosity, and red intensity variables of sweet potato tuberous from plants treated with calcium oxide particle films at three concentrations (5, 10, and 15% w/v) and control (water). Values represent mean (±standard deviation). We did not find differences among treatments: blue/yellow coordinate (F = 1.79; df = 3, 9; p = 0.21), chroma (F = 0.67; df = 3, 9; p = 0.58), hue angle (F = 1.97; df = 3, 9; p = 0.19), luminosity (F = 2.03; df = 3, 9; p = 0.18), and red intensity (F = 2.30; df = 3, 9; p = 0.15), Figure S2: calcium (%), firmness (N), pH, starch content (%), titratable acidity (g 100g), and total soluble solids (^{0}Brix) of sweet potato tuberous from plants treated with calcium oxide particle films at three concentrations (5, 10, and 15% w/v) and control (water). Values represent mean (± standard deviation). We did not find differences among treatments: calcium content (F = 74.21; df = 3, 9; p < 0.0001), firmness (F = 0.92; df = 3, 9; p = 0.47), pH (F = 1.09; df = 3, 9; p = 0.40), starch content (F = 2.42; df = 3, 9; p = 0.29) titratable acidity (F = 1.11; df = 3, 9; p = 0.39), and total soluble solids (F = 1.09; df = 3, 9; p = 0.41).

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Conflicts of Interest: The authors declare no conflict of interest.

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