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Investigation note

Carbon fertilization in medium-tech greenhouses

Enrique Rico-García[1,§]
Adrián Esteban Ortega-Torres[1]
Adán Mercado-Luna[1]
Ramón Gerardo Guevara-González[1]
Irineo Torres-Pacheco[1]

1 1 Departamento de Biosistemas-Facultad de Ingeniería-Universidad Autónoma de Querétaro. Querétaro, México. CP. 76010. Tel. 442 1921200, ext. 6023. (adrianesotorres@gmail.com; adan.mercado@uaq.mx; ramon.guevara@uaq.mx; irineo.torres@uaq.mx).

Autor para correspondencia. ricog@uaq.mx.

Abstract

Carbon fertilization is used in protected agriculture to increase crop productivity. Medium-tech greenhouses do not have climate control equipment other than the electric or manual opening of windows. In these greenhouses, in general, the values of temperature and relative humidity of the air are not ideal for the photosynthesis of the crop in the daytime period between 10:00 am and dusk. The study of a climate database of a medium-tech greenhouse showed that, in the mornings, there are suitable climate conditions for the photosynthesis of the crop. In this work, an experiment was carried out with two medium-tech greenhouses of 108 m^2; tomatoes (*Solanum lycopersicum*) and cucumbers (*Cucumis sativus*) were grown in both greenhouses; one received carbon fertilization between 7:30 and 9:00 h, whereas the other was maintained with traditional management, without CO_2 injection. This study aimed to evaluate the effect of carbon fertilization on crop productivity, expecting significant increases. The results showed increases in weekly productivity of 28% to 59% in tomatoes. There were no significant differences in productivity for cucumbers.

Keywords:

adequate internal climate, CO2 injection, crop productivity.

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According to Juárez-López *et al*. (2011), greenhouses are classified as low, medium and high technology according to their level of technification as follows: low technology, their internal climate is 100% dependent on the external climate, they use simple technologies similar to those used in open-field cultivation; medium technology, it corresponds to battery greenhouses that are semi-air-conditioned, with automatic irrigation and they can be in soil or hydroponics; high technology, they are facilities that have automated climate control (greater independence from the external climate) computerized drip irrigation, and CO_2 injections, and use sensors and devices that operate irrigation and ventilation systems, thermal screens, lighting, and hydroponics.

Carbon fertilization in greenhouses is a technique that has been used for a long time in protected agriculture (Mortensen, 1987; Xin *et al*., 2015; Reinoso-Moreno *et al*., 2024). This action has been successfully used to increase productivity between 30% and 70% in tomatoes (Martzopoulou *et al*., 2020). Usually, the injection of CO_2 is done in high-tech greenhouses, which have climate control equipment (de Anda and Shear, 2017).

Medium-tech greenhouses tend to be hot during the daytime, which causes low relative humidity inside the greenhouse, so usually, the temperature and humidity in the air are outside the appropriate ranges to carry out the potential photosynthesis of the crop. Schmidt *et al*. (2008) found that, for a tomato crop, the photosynthetic efficiency of the crop increased in the range of 20-24 °C for temperature and 80 to 90% for relative humidity. Normally, in medium-tech greenhouses, these climate conditions inside the greenhouse are not achieved during the daytime period, especially during the hottest months (April to June).

Climate data for a medium-technology greenhouse on the Amazcala *Campus* of the Autonomous University of Querétaro indicated that there are favorable conditions for photosynthesis during the early hours of the morning; in addition, in the cultural management of these greenhouses, the windows are kept closed during the night period and early hours of the morning, which led to the proposal that carbon enrichment can be carried out during the first hours of the day, taking advantage of the natural conditions of the internal microclimate of the greenhouse, with the intention of increasing the productivity of the crops.

Location

The experiment was conducted at the Amazcala *Campus* of the Faculty of Engineering of the Autonomous University of Querétaro. It is located in the municipality of El Marqués, Querétaro, Mexico, 20° 42' 21" north latitude, 100° 15' 36" west longitude and 1 923 masl.

Selected crops

We worked with two crops: tomato (*Solanum lycopersicum*) of the Córdoba variety of the Premier seeds brand and cucumber (*Cucumis sativus*) of the Lisboa variety of the Bejo brand; both crops were non-grafted plants. These crops were selected for their economic importance and high market demand.

Germination

The seeds were germinated in peatmoss inside 128-cavity trays inside a greenhouse for seedling production on the Amazcala *Campus*; the trays remained covered for about three days in order to retain moisture and accelerate the germination process; the tomato seeds were sown on February 9, 2018, and the cucumber seeds on March 13, 2018, leaving this time due to the faster cycle of the cucumber compared to tomato.

Transplantation

The tomato was transplanted on March 18 and the cucumber on April 2. Using a hydroponic system with 10 L co-extruded polyethylene bags with a double layer, black inside to prevent the passage

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of light and not damage the root and white on the outside in order to reflect the greatest amount of radiation and thus avoid heating the substrate. The substrate used was tezontle with a granulometry from 1 mm to 1 cm.

Nutrition and cultural management of crops

For crop nutrition, a drip irrigation system with 4 L h^{-1} emitters was used. There was a drainage of 20 to 30%. The nutrient solution was defined by looking for one that would fit the two types of crops because they shared the same irrigation system (Table 1), pH of 5.5 and EC of 2.82 dS m^{-1}.

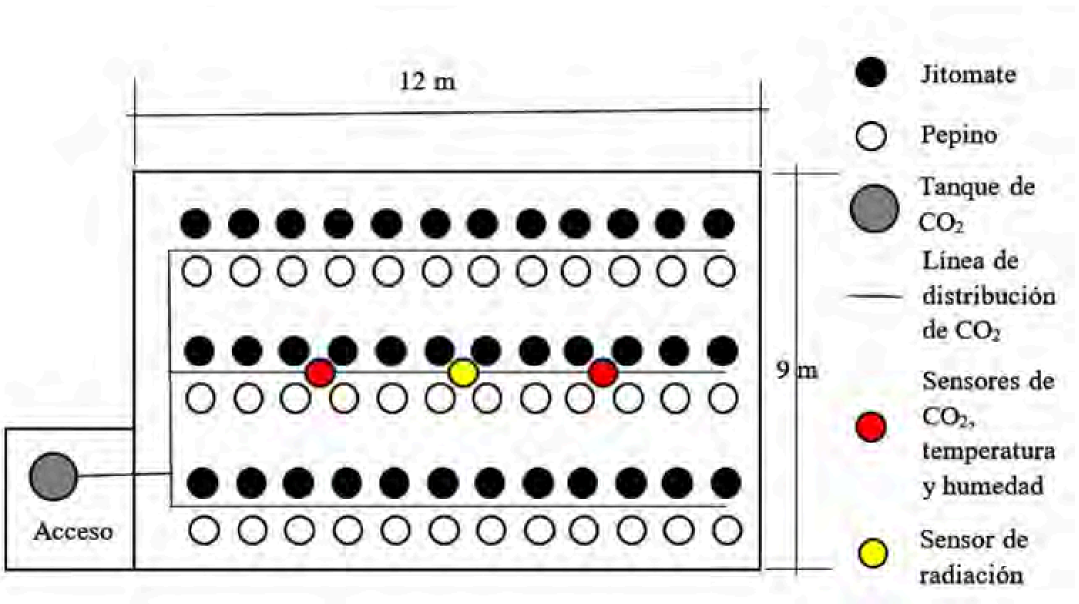
Table 1. Nutrient solution.

Unit	$-NO_3^-$	$H_2PO_4^-$	SO_4^{--}	Ca^{2+}	Mg^{2+}	K^+
ppm	930	193.94	240.15	200.4	36.45	351.9
	Fe	Cu	Mn	Bo	Zn	
ppm	3	0.02	0.62	0.44	0.11	

The experiment was carried out in two adjoining greenhouses, one worked as a control (without carbon fertilization), whereas the other was the treatment (with carbon fertilization). The dimension of each of the greenhouses was 9 (width) x 12 (length) x 4.5 (height to gutter) meters, covering an area of 108 m^2; each greenhouse had a total of 162 plants (81 tomato plants and 81 cucumber plants), obtaining a planting density of 1.5 plants m^{-2}.

The arrangement of the crops was longitudinal with three double tomato-cucumber rows for both greenhouses (Figure 1). The development of the two crops was worked on one stem, eliminating the axillary shoots. During the harvest stage, one to two fruits per cucumber plant and one bunch per tomato plant were cut weekly.

Figure 1. Greenhouse scheme with carbon fertilization, crop distribution, and measurement sensors.



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CO_2 injection

A carbon enrichment system was installed in one of the greenhouses, which consisted of a 25 kg liquid CO_2 tank with a solenoid valve, a pressure gauge, and an arrangement of distribution lines made of 13 mm polyethylene hose drilled every 50 cm with a 2 mm metal drill bit (Figure 1). Carbon enrichment began on April 25, 2018, during the flowering stage of the two crops, every day until the end of the experiment, June 20, 2018. The CO_2 was injected into the greenhouse until it reached an approximate concentration of 800 ppm, between 7:30 and 9:00 h; in general, to maintain the CO_2 level in the indicated time, it was necessary to make three to four injections intermittently to get as close as possible to 800 ppm.

Carbon enrichment was done only if the following climate conditions inside the greenhouse were met radiation greater than zero, relative humidity between 65 and 90%, air temperature between 10 and 28 °C and that the windows remained closed to minimize CO_2 loss through ventilation.

If any of the conditions were not met, CO_2 was not injected, and when the temperature exceeded 28 °C in the internal air due to solar radiation, the side and zenithal windows were opened, stopping the injection of CO_2 for the rest of the day. All these actions were done manually. The climate conditions inside the greenhouse for carbon fertilization were defined considering the climatic conditions referred to in Schmidt *et al*. (2008).

Measurement system for climate variables inside greenhouses

For the monitoring system of the climatic conditions, we worked with two FYAD 00 CO2B10 CO_2 sensors distributed equally in the greenhouse, two FHAD462 temperature and relative humidity sensors connected to the Almemo® 25904AS datalogger, all the equipment of the Alhborn brand; a 36681-radiation sensor was also installed together with the Spectrum® WatchDog 1000 series measuring instrument.

Phenological response variables

Measurements were made on three dates, June 6, 13, and 20, 2018, in triplicate for each of the greenhouses, for productivity, dry weight and leaf area. For productivity of the fruit produced: in cucumbers, the weight of each fruit was obtained separately and in tomatoes, the bunches were weighed. The harvested fruits were cleaned and weighed at room temperature; the samples were placed in the center of the scale plate to avoid vibrations when removing the sample; a duplicate of the weighed samples was made, and the values were immediately noted in the logbook.

For dry matter, the fresh sample was weighed and then dried at a constant temperature of 100 °C in a Riossa® HCF-41 drying oven until constant weight was obtained. This was done for the plant without including the fruits; that is, stems and leaves, so this measurement implied removing the entire plant (destructive test). The weight measurements were made on a Torrey® L-EQ digital scale.

The leaf area of each plant was determined via digital image processing. The leaves of the crops were cut and arranged on a white surface and then digital photographs were taken at a fixed distance so as not to lose the calibration with a known area. Finally, the leaf area was determined with a programming code in Matlab, which correlates the number of pixels with the known area to calculate the area of the leaves in the photograph (Rico-García *et al*., 2009).

The statistical analysis was carried out by means of a one-way Anova and a mean comparison test, Tukey ($p < 0.05$), comparing each of the variables with and without carbon fertilization on the same measurement dates. The OriginPro software was used for both statistical analysis and graph creation.

In the productivity of the tomato crop, there were significant differences for the first and second weeks, whereas, for the third, there were none; however, the trend was maintained. Compared to crops without carbon fertilization, tomato productivity increased by 59%, 41%, and 28% for the first, second, and third weeks of harvest, respectively. These results are consistent with Martzopoulou et al. (2020).

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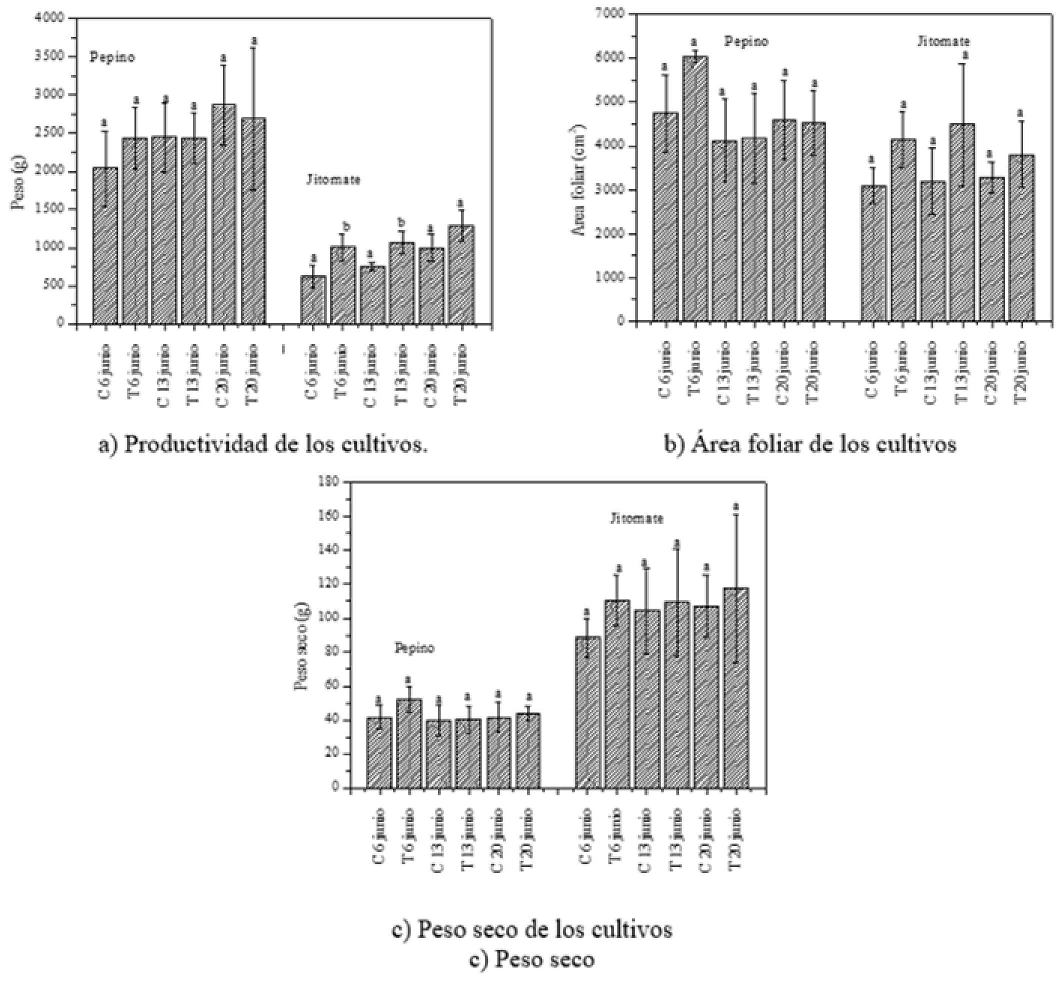
Regarding cucumber productivity, there were no significant differences, nor can we see a trend that demonstrates that CO_2 injection increases productivity (Figure 2a); this does not coincide with Sánchez-Guerrero *et al*. (2005); Martzopoulou *et al*. (2020), where they report increases of 25%to 50% for cucumber. For the variables of dry weight and leaf area, there were no significant differences in both crops. Nonetheless, a positive trend is maintained in both variables (Figures 2b and 2c). This coincides with what was reported by Sánchez-Guerrero *et al*. (2005) in that the effect of carbon enrichment expresses itself in the biomass of the fruit whereas the leaf area is not increased.

Figure 2. Crop response variables. Compare only the same dates. C= control; T= treatment.



According to the results, carbon fertilization during the first hours of the day increased productivity for tomato crops in medium-tech greenhouses; this showed that the temperature and internal air humidity conditions, which occur naturally in the morning in adequate ranges, can be taken advantage of to enhance the photosynthesis of the crop. This would increase productivity from 20 kg m^{-2} (de Anda and Shear, 2017) for a medium-tech greenhouse to 28 kg m^{-2} of tomatoes per cycle.

In order for the injection of CO_2 into medium-tech greenhouses to be a reality, systems such as those described must be developed. Reinoso Moreno *et al*. (2024) studied tomato production in

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a pilot greenhouse by doing carbon fertilization with CO_2 from biomass combustion, they reported an increase in productivity of 18% compared to another greenhouse without carbon fertilization; systems like this can reduce the costs of carbon fertilization. Bao *et al*. (2018) points out that CO_2 capture systems represent an option that should be developed, explaining that the same horticultural production greenhouses can function as CO_2 sequestering structures and use it as an input in production. Oreggioni *et al*. (2019) presented the use of CO_2 produced by biodigesters for carbon enrichment in greenhouses; they even report that this action is more efficient than the storage of CO_2 in the earth's crust to mitigate the effects of climate change. Hao *et al*. (2020) presented a similar scenario, reporting that the use of CO_2, a by-product of the biodigestion of agricultural waste, increases the productivity and quality of greenhouse tomatoes.

Conclusions

The results of this work indicate that tomato production in medium-tech greenhouses increases with carbon enrichment during the mornings between 7:30 and 9:00 h. Nevertheless, there was no increase for cucumber crops.

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