agronomy

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Active Control of Greenhouse Climate Enhances Papaya Growth and Yield at an Affordable Cost

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Abstract: Papaya is a tropical fruit crop that in subtropical regions depends on protected cultivation to fulfill its climate requirements and remain productive. The aim of this work was to compare the profitability of different climate control strategies in greenhouses located in subtropical areas of southeast Spain. To do so, we compared papayas growing in a greenhouse equipped with active climate control (ACC), achieved by cooling and heating systems, versus plants growing in another greenhouse equipped with passive climate control (PCC), consisting of only natural ventilation through zenithal and lateral windows. The results showed that ACC favored papaya plant growth; flowering; fruit set; and, consequently, yields, producing more and heavier fruits at an affordable cost. Climate control strategies did not significantly improve fruit quality, specifically fruit skin color, acidity, and total soluble solids content. In conclusion, in the current context of prices, an active control of temperature and humidity inside the greenhouse could be a more profitable strategy in subtropical regions where open-air cultivation is not feasible.

Keywords: *Carica papaya* L.; protected cultivation; climate control strategies; active climate control; passive climate control; profitability

Citation: Salinas, I.; Hueso, J.J.; Cuevas, J. Active Control of Greenhouse Climate Enhances Papaya Growth and Yield at an Affordable Cost. *Agronomy* **2021**, *11*, 378. https://doi.org/10.3390/agronomy11020378

Academic Editor: Dimitrios Savvas

Received: 2 February 2021
Accepted: 17 February 2021
Published: 20 February 2021

1. Introduction

Papaya (*Carica papaya* L.) is one of the most consumed fruits in the world. The latest data in 2019 reported a total production of more than 13.7 million tons in more than 460,000 ha [1]. As a tropical crop, papaya is very demanding regarding climate requirements. Its temperature range for correct development is 21–33 °C, with 25 °C being the optimum value. Temperatures below 20 °C or above 35 °C cause diverse flower malformations, reducing yield and fruit quality. Temperatures below 15 °C compromise papaya production, making it unsuitable for open field cultivation, whereas, on the other hand, temperatures above 30 °C limit photosynthesis and hinder the fertilization of the flowers, thus reducing yields [2–4]. In addition, papaya requires the humidity level to be between 60 and 85% to ensure adequate growth [2]. The lack of humidity reduces fruit set and causes premature leaf drop. Low relative humidity and high temperatures also stimulate the proliferation of red mites [5]. On the contrary, humidity that is too high favors flower malformations and misshapen fruit [6], as well as fungal diseases [7]. On the contrary, humidity control to obtain an adequate vapor pressure deficit (VPD) in summer can improve fruit set and yield [4,8] and reduce mite pressure [9].

Despite its tropical origin, papaya in its cultivation is feasible and profitable in subtropical regions [10–12]. Areas such as the Canary Islands and peninsular Spain have for this reason shown an increasing interest in this crop. However, in these regions, protected cultivation is mandatory since the temperatures are often outside the papaya optimal range, by excess in summer and by default in winter. Plastic greenhouses with only passive climate control by natural ventilation are the most common cultivation systems in Spain [11]. However, papaya yield and quality can be improved using heating and refrigeration, although the profitability of such measures is still to be proved. Considering the above questions, the objective of this research was to compare plant growth, fruit production, and quality under two different cultivation scenarios, passive versus active climate control, in order to determine the most profitable strategy in plastic greenhouses of southeast Spain.

2. Materials and Methods

2.1. Site and Plant Material

This study was carried out in the Cajamar Experimental Station "Las Palmerillas", located in El Ejido (Almería, Spain) (2°43′ W, 36°48′ N, and 151 m above sea level). Experimental plants were grown in a multi-tunnel 37.5 µm thick polyethylene plastic greenhouse, with 3.4 m high in the eaves and 5.4 m in the ridge. This greenhouse was divided into 2 modules with 2 different climate control strategies, one based on a passive climate control (PCC) and the other on an active climate control (ACC). PCC takes advantage of the natural ventilation to cool the atmosphere within the greenhouse through 5 zenithal windows and a lateral panel. Windows open automatically when the temperature hits 24 °C. In addition, and as usual in Almería greenhouses, roof whitening was performed on 1 June 2017 using 25 kg of Whitefix (Royal Brinkman's, Gravenzande, the Netherlands) diluted in 300 L of water. ACC strategy incorporated, in addition to the natural ventilation, a heating system and a cooling system. The heating system consisted of a flow hot air Ermaf RGA95 (Elster), with diesel as fuel. The heating system was activated when temperature was ≤15 °C during the cold period of the first season (November 2016 to March 2017), and ≤12 °C during the cold period of the second season (November 2017 to March 2018). The cooling system consisted of a low-pressure (4 bars) nebulization system CoolNet Pro (Netafim), with 5,5 L h^{-1} double emitter spaced 0.1 nozzles m^{-2} and 1 L m^{-2} h^{-1} flow. Nebulization was activated when relative humidity was below 60%.

"Siluet" was the cultivar selected for the study, after considering its market demands, productive potential, and fruit quality [13]. Hermaphrodite plants of "Siluet" were selected at seedling stage in the nursery employing molecular sex-determining procedures, using molecular markers based on single nucleotide polymorphisms (SNPs). The plantation, with seedlings spaced 2.5 × 1.5 m, was carried out on 6 April 2016, and the trees were pulled out at the end of the experiment on 6 July 2018. Irrigation and fertilization were identical in both modules and followed recommendations for papaya cultivation in our local conditions. Misshapen flowers and non-commercial fruits were removed throughout the cycle, as well as the blades of senescent leaves. Pest and disease control was carried out following Integrated Pest Management guidelines.

2.2. Climate Measurements: Plant Growth Conditions

Climate data were recorded in both modules throughout the entire growing cycle. A ventilated aspyropsychrometer with a PT-100 probe was used to record dry bulb and wet bulb temperatures, and a Priva climate controller collected information and managed the opening and closing of the windows. Considering these records, we calculated maximum, average, and minimum temperatures and relative humidity and compared them between modules.

2.3. Plant and Fruit Measurements: Plant Growth, Yields, and Fruit Quality

Plant height from ground to the top of the canopy, using a graded bar, and trunks perimeter at 15 cm from the ground, using a seamstress tape ruler, were seasonally recorded. The distance from the ground to the first flower and to the first fruit were also recorded using a seamstress tape ruler. All these measurements were expressed as centimeters. Seasonal frequency of elongata, pentandric and carpelloid hermaphrodite flowers, and female and functionally male flowers [14] were determined and expressed as percentage inspecting the total number of open flowers in specific dates of autumn (November 2016), winter (January 2017), spring (May 2017), and summer (July 2017), in order to elucidate the climate influence on the sexual expression of flowers.

Total and commercial yields, discards (percentage of fruits lighter than 200 g and non-commercial misshapen fruits that were not initially detected), the number of fruits per plant, and their average weight were all compared between modules. Fruits were harvested once or twice a week, depending on the season, when 50% of the skin reached yellow color. Monthly yields were finally established and represented.

Fruit quality was seasonally evaluated in 24 fruits per treatment harvested between August 2017 and May 2018, when 50% of yellow color was reached in the fruit skin, which is the recommended maturity stage for short distance markets [15]. Fruit weight (g) using a precision balance (d = 0.1 g), and length, from the insertion point of the peduncle into the fruit to the scars of the flower vestiges, as well as the maximum equatorial diameter and cavity width (in cm) were measured with a digital caliper. Pulp firmness in 2 opposite equatorial zones was assessed after peel removal using a digital firmness texter (model Pénéfel DFT 14, Agro-Technology, Forges Les Eaux, France) and expressed as newtons. Total soluble solids content (TSS) and titratable acidity (TA) were determined using the juice of each single fruit. TSS was measured using a digital refractometer (model PR-101, Atago Co., Tokyo, Japan) and expressed as °Brix. TA was measured by titration with 0.1 N NaOH and phenolphthalein as indicator and expressed as grams of citric acid per liter of juice. In addition to the seasonal fruit quality evaluations, TSS of fruits of both modules were compared along the cycle. Finally, skin and pulp color were determined with a colorimeter (model CR-400, Konica Minolta, Co., Tokyo, Japan) in 3 positions of the equatorial zone of each sampled fruit. The results were expressed considering hue angle (hue°), which indicates the color tone of the fruit. A hue angle of 120° corresponds to yellowish green color, 90° to yellow color, 60° to yellow-orange color, 45° to orange color, and 0° to red color.

2.4. Profitability Analysis

A profitability analysis was carried out, comparing the 2 climate control strategies for a 26-month cultivation cycle. In this analysis, production costs were estimated including labor force (management and harvest); cultivation inputs for irrigation, fertilization, and pest and disease control; and indirect costs associated with the depreciation of the infrastructure (greenhouse and equipment). In the comparison, we assumed the same production costs (expressed as EUR per kg of commercial yield) in both modules, although harvesting might be more efficient with a higher yield (ACC). Fuel consumed and the amortization for the heating and fogging equipment were charged only to ACC. After this, we calculated the price at which the obtained yields in each climate strategy could be profitable. The break-even point was also calculated, such as the selling price at which income was equal to expenses for each climate strategy. Finally, the resulting gross margin was calculated for a regular market price of EUR 1.30 kg^{-1}.

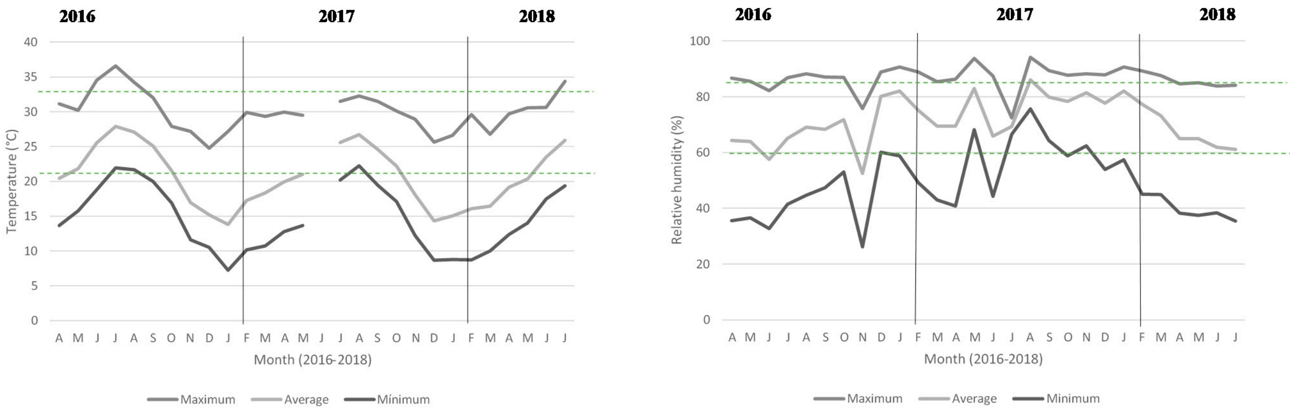
2.5. Statistical Analysis

A randomized complete design with 6 replicates per module was designed. Each replicate was constituted by a tree row in which the 4 central trees were selected for measurements. Data were subjected to analysis of variance (ANOVA), and the means were separated by Tukey's test using Statistix 8.0 software (Analytical Software, Tallahassee, Florida, USA).

3. Results

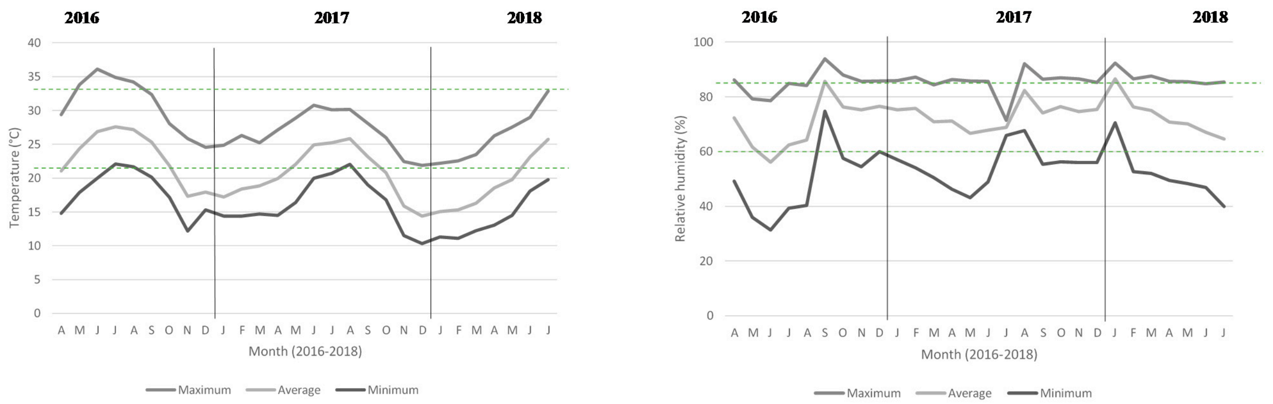
3.1. Climate Measurements: Plant Growth Conditions

Temperature and relative humidity recorded throughout the growing cycle in the PCC module and the ACC module are represented in Figures 1 and 2, respectively. Minimum temperatures reached in winter in PCC module were at times too low considering papaya crop requirements. The minimum temperature in PCC was recorded in January 2017 (7.2 °C), while in the second winter, the minimum temperature was around 8 °C (Figure 1). ACC modified the conditions inside the greenhouse. In this regard, the heating system made it possible to attenuate low temperatures in winter, especially in the first year when a set point of 15 °C was established. The minimum temperature in ACC was 14.4 °C in the first year. In the second winter, we established the set point at 12 °C, and minimums temperatures were sometimes between 10 and 11 °C. ACC also reduced too high temperatures in summer. The nebulization effect was observed, especially in the second summer, when the maximum temperatures dropped by 2–3 °C in the ACC module compared to the PCC module (Figures 1 and 2). Relative humidity oscillations were also lower in ACC (Figures 1 and 2).



(**a**) (**b**)

Figure 1. (**a**) Maximum, average, and minimum temperatures and (**b**) relative humidity calculated in the passive climate control module. The horizontal dotted lines mark the optimal temperature and relative humidity ranges for papaya crop, according to Nakasone and Paull (1998) [2] and Campostrini and Glenn (2007) [4].



(**a**) (**b**)

Figure 2. (**a**) Maximum, average, and minimum temperatures and (**b**) relative humidity calculated in the active climate control module. The horizontal dotted lines mark the optimal temperature and relative humidity ranges for papaya crop, according to Nakasone and Paull (1998) [2] and Campostrini and Glenn (2007) [4].

3.2. *Plant and Fruit Measurements: Growth, Yields, and Fruit Quality*

Climate control strategies modified plant growth and height. The plants of ACC were taller than those of PCC module. Significant differences in plant height were obtained in all sampling dates (Figure 3). During the initial period (April–October 2016), plant growth was rapid in both environments, but especially in ACC, where plants reached 225 cm at the top compared to 180 cm in PCC (Figure 3). During winter, reduced growth took place but growth was reactivated between April and October 2017 (380–562 dap). At the end of July, plant height in ACC was 390 cm, while in PCC it was just 270 cm, in part because PCC plants only grew during spring and part of the summer (Figure 3). At the end of the second winter, in the last period of the life span of the crop, the plants reassumed growth. At the end of the cycle (821 dap), just before pulling out the trees, PCC plants were 300 cm tall while ACC plants reached 434 cm, that is, they were almost 50% taller (Figure 3).

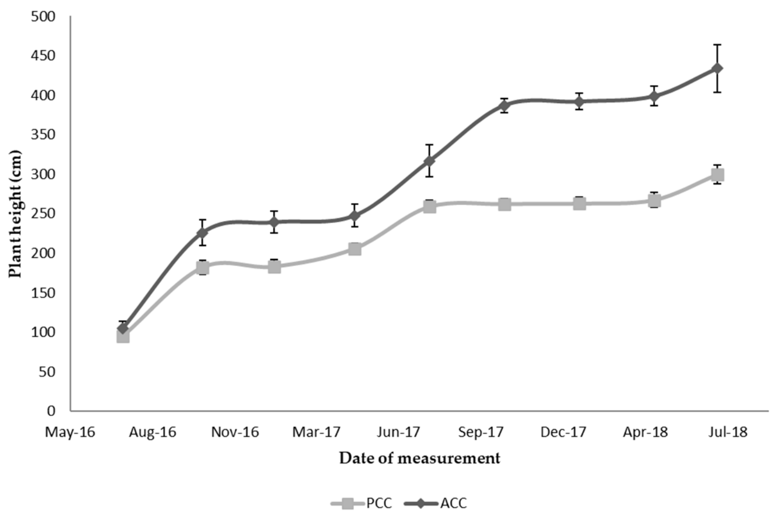


Figure 3. Plant height changes in "Siluet" papayas grown in passive climate control (PCC) and active climate control (ACC) modules. Symbols represent the mean values of plant height while bars represent the standard deviations.

Trunk growth was also modified by climate control strategies. Trunks were thicker in the plants of the ACC module than in those of the PCC module. Significant differences between treatments were established in the first months of the plantation and maintained thereafter. Contrary to plant height, trunks did not stop growing at any moment, not even in the coolest months of winter. At the end of the experiment, trunk perimeter of plants developed under ACC was 63 cm on average, while those under PCC reached 58 cm (Figure 4).

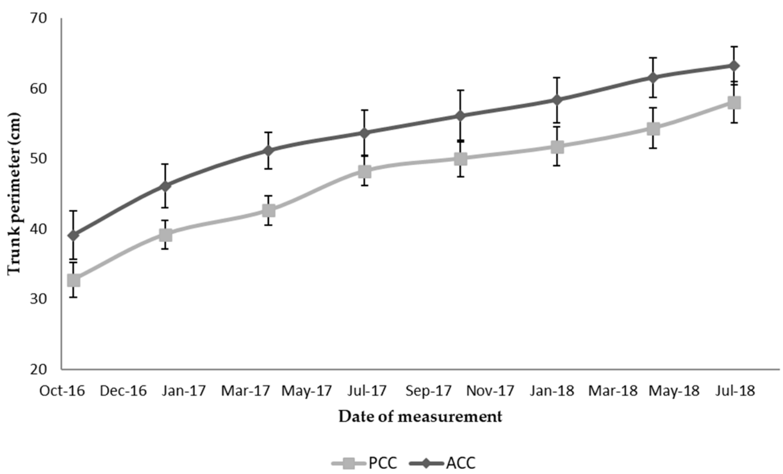


Figure 4. Trunk perimeter changes in "Siluet" papayas grown in passive climate control (PCC) and in active climate control (ACC) modules. Symbols represent the mean values of plant trunk perimeter while bars represent the standard deviations.

Distance from the ground to the first flower was not modified by climate control strategies, occurring in both modules at around 59 cm (Table 1). However, in the PCC module, the flowers of the following nodes aborted, and thus the first fruit arose at 104 cm from the ground, a significantly higher height than in plants grown under ACC (81 cm), where flower abortion was reduced (Table 1), making the portion of the trunk bearing fruits longer.

Table 1. Distance from the ground to the first flower and to the first fruit in "Siluet" papaya grown in PCC and ACC modules.

Climate Control Strategy	Distance to First Flower (cm) *	Distance to First Fruit (cm) *
PCC	58.5 [a]	104.1 [a]
ACC	58.7 [a]	80.9 [b]

Different letters in the same column indicate statistically significant differences between climate control strategies (Tukey's test $p < 0.05$). * From the ground.

The seasonal frequency of the different floral types of papaya was determined in both modules by inspecting the total number of open flowers in a given date. The results showed that elongata hermaphrodite and functionally male flowers were the only types of flower present in those sampling days (Figure 5). Other types of flowers, especially pentandric and carpelloid flowers, appeared only on specific dates, demonstrating the large influence of the environmental factors. The highest frequency of flowers of commercial interest forming nice-shaped fruits (hermaphrodite elongata) was observed in spring (67% in PCC versus 100% in ACC) (Figure 5). In autumn and summer, the distribution of the floral typology was similar in both environments, with 50% of elongata and functionally male flowers in PCC versus 60% and 40%, respectively, in ACC (Figure 5). In winter, elongata flowers were again more frequent in ACC (Figure 5).

(**a**) (**b**)

Figure 5. Seasonal frequency (%) of elongata hermaphrodite flowers (orange) that later on will produce fruits with commercial interest, and sterile, functionally male flowers (dark blue) found in "Siluet" papaya grown in (**a**) passive climate control (PCC) and in (**b**) active climate control (ACC) modules. Rings from inside to outside: autumn (November 2016), winter (January 2017), spring (May 2017), and summer (July 2017).

ACC advanced flowering and fruit setting, but also fruit ripening and harvest. Harvest started in December 2016 (8 months after plantation) in the ACC module, while in the PCC module, harvest began 3 months after (March 2017). Cumulative yield at the end of the cycle clearly summarizes the positive effects of ACC. Total yield was 33.5 kg m^{-2} in the ACC module but only 14.1 kg m^{-2} in PCC, with commercial yield also being much higher (Table 2). These yields were in accordance with the number of fruits harvested and with the average weight. In the ACC module, nearly double the number of fruits per plant were collected in comparison to PCC (Table 2). The average fruit weight was also higher (Table 2). Discarded fruits were below 5% in both modules (Table 2).

Table 2. Total and commercial yield, discards (%), fruit number per plant, and fruit weight in "Siluet" papaya grown in passive climate control (PCC) and active climate control (ACC) modules.

Climate Control Strategy	Total Yield (kg m^{-2})	Commercial Yield (kg m^{-2})	Discards (%)	Fruits Per Plant	Fruit Weight (g)
PCC	14.1 ^{b}	13.6 ^{b}	3.5 ^{a}	52 ^{b}	983 ^{b}
ACC	33.5 ^{a}	32.1 ^{a}	4.4 ^{a}	101 ^{a}	1173 ^{a}

Different letters in the same column indicate statistically significant differences between climate control strategies (Tukey's test $p < 0.05$).

Once started, harvesting continued uninterruptedly until the end of the experiment in both modules, although monthly yield was always higher in ACC (Figure 6). Harvest peaks were observed in spring and summer in both modules, although commercial yield was lower and less prolonged in PCC than in ACC, where more than 3 kg m^{-2} per month was harvested and overpassed some months (Figure 6). Harvest remained fairly low between November and February (Figure 6).

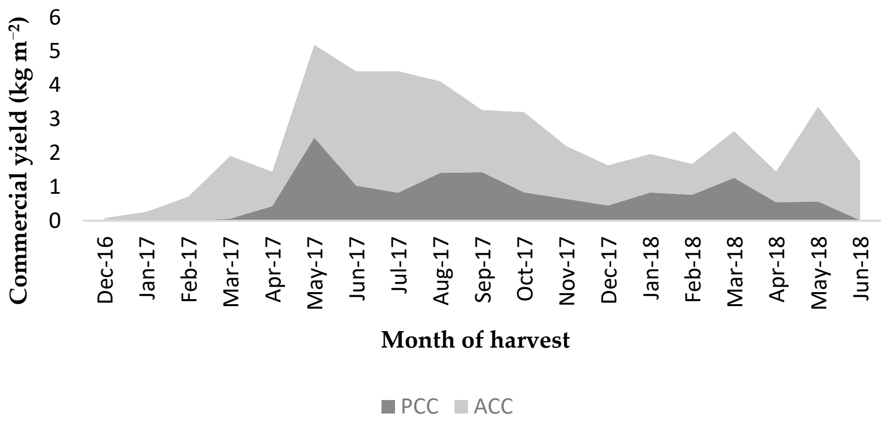


Figure 6. Monthly commercial yields of "Siluet" papaya grown in passive climate control (PCC) and active climate control (ACC) modules.

Fruit quality evaluations in "Siluet" papayas harvested when 50% of the skin had yellow color revealed minor differences depending on the climate control strategy used and larger depending on the time in which the fruit set and ripened (time from fruit set to harvest is about six months). Fruit size was generally greater in ACC, especially in terms of weight. In summer and spring, ACC fruits weighed between 1100 and 1250 g, while those of PCC were between 700 and 1250 g, with significant differences (Table 3). The length of fruits was similar in both modules (20–22 cm in ACC vs. 19–23 cm in PCC), with longer fruits obtained in summer and spring in ACC; however, on the contrary, the longest fruits in winter were those of PCC (Table 3). The diameter was slightly greater in ACC fruits, as was the internal cavity. However, significant differences were limited to the summer (Table 3).

Fruit firmness was highly variable depending on the season, being around 30 N in summer, 60–70 N in winter, and 40–50 N in spring (Table 4). Sugar content was not substantially modified by climate control strategies, yet TSS content was more stable in PCC (10–11 °Brix) than in ACC fruits (9.5–11.5 °Brix) (Table 4). Nevertheless, TSS content was above the minimum required for the commercialization of papaya (10 °Brix) almost always, regardless climate control strategy used. In spring (May–June) and winter (January–February), TSS fell below 10 °Brix, periods when we evaluated fruits setting during the previous winter and fruit ripening during the coldest months, respectively (Figure 7). Fruit acidity was quite unreliable. However, significant differences were observed in spring, with higher values in ACC fruits (Table 4). Fruits harvested in summer (but setting in winter) were the smallest and the sweetest, regardless of the climate strategy followed (Tables 3 and 4). Finally, skin and pulp color varied more depending on the season and less depending on the greenhouse module (Table 4). The highest hue° values in the skin (less orange fruits) were obtained in winter and spring (Table 4). Regarding pulp color, ACC fruits were more orange than those of PCC, finding significant differences only in summer (Table 4).

Table 3. Fruit size parameters in "Siluet" papaya grown in passive climate control (PCC) and active climate control (ACC) modules (fruit harvested in summer 2017, winter and spring 2018 when skin was 50% yellow).

	Weight (g)		**Length (cm)**		**Diameter (cm)**		**Cavity Width (cm)**	
	PCC	ACC	PCC	ACC	PCC	ACC	PCC	ACC
Summer	724 ^{b}	1100 ^{a}	18.6 ^{b}	21.6 ^{a}	8.8 ^{b}	10.4 ^{a}	3.9 ^{b}	5.4 ^{a}
Winter	1241 ^{a}	1210 ^{a}	23.4 ^{a}	21.5 ^{b}	11.0 ^{a}	10.9 ^{a}	6.3 ^{a}	5.8 ^{a}
Spring	956 ^{b}	1224 ^{a}	19.4 ^{b}	21.1 ^{a}	11.4 ^{a}	12.0 ^{a}	5.8 ^{a}	6.2 ^{a}

Different letters in the same row indicate statistically significant differences between climate control strategies (Tukey's test $p < 0.05$). Autumn comparison was not possible because of the low number of fruits harvested in those months in PCC.

Table 4. Fruit quality in "Siluet" papaya grown in passive climate control (PCC) and active climate control (ACC) modules (fruit 50% skin yellow harvested in summer 2017, winter and spring 2018).

	Firmness (N)		**TSS (°Brix)**		**TA (g Citric Acid L^{-1})**		**Skin Color (hue°)**		**Pulp Color (hue°)**	
	PCC	ACC	PCC	ACC	PCC	ACC	PCC	ACC	PCC	ACC
Summer	30.0 ^{a}	27.1 ^{b}	11.1 ^{a}	11.5 ^{a}	1.0 ^{a}	1.0 ^{a}	83.6 ^{a}	86.3 ^{a}	50.0 ^{a}	46.1 ^{b}
Winter	66.8 ^{a}	65.6 ^{a}	9.9 ^{a}	9.6 ^{a}	0.7 ^{a}	0.8 ^{a}	107.0 ^{a}	107.8 ^{a}	69.3 ^{a}	65.4 ^{a}
Spring	49.4 ^{a}	43.6 ^{a}	10.7 ^{a}	10.9 ^{a}	0.8 ^{b}	1.0 ^{a}	102.9 ^{a}	101.9 ^{a}	52.2 ^{a}	51.3 ^{a}

Different letters in the same row indicate statistically significant differences between climate control strategies (Tukey's test $p < 0.05$).

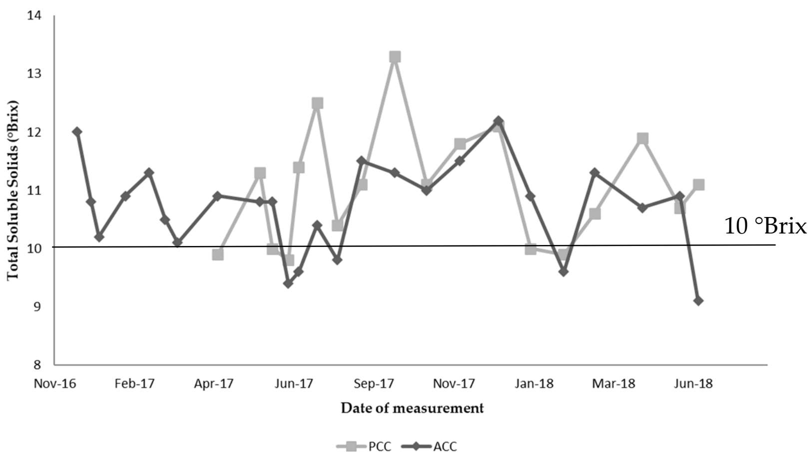


Figure 7. Total soluble solids content (TSS) changes in fruits harvested in passive climate control (PCC) and active climate control (ACC) modules throughout the growing cycle. The horizontal line marks 10 °Brix value, commonly referred as the minimum required for papaya commercialization.

3.3. *Profitability Analysis*

An analysis of profitability was carried out to compare both climate control strategies. The cultivation costs were estimated near EUR 0.60 kg^{-1}. Once this cost was calculated, a price of EUR 0.90 kg^{-1} was established as the minimum to select ACC considering the yields obtained. This means that, with our yields, gross margin was EUR 4 m^{-2} in both treatments at that price. With prices above EUR 0.90 kg^{-1}, the margin achieved with ACC resulted in being higher than with PCC, as with prices below EUR 0.90 kg^{-1}, PCC would result more profitable. The break-even point, such as the selling price at which income equals expenses, was EUR 0.60 kg^{-1} for PCC (the cultivation costs estimated) and EUR

0.78 kg^{-1} for ACC (the cultivation costs plus active climate control costs). Finally, the resulting gross margin calculated for a regular market price of EUR 1.30 kg^{-1} was over EUR 17 m^{-2} for ACC, compared to EUR 10 m^{-2} for PCC (78% less).

4. Discussion

The cultivation of papaya under plastic greenhouses equipped with basic passive climate control is a profitable enterprise for farmers in southeast Spain, representing a better alternative to vegetable production [11,13]. In this regard, gross margin of EUR 10 m^{-2} compares very favorably with the margins obtained by farmers producing vegetables under plastic. However, an enhancement of climate control by heating during the coolest months of winter and by fogging during the hot months of summer increased profits in more than 70% to more than EUR 17 m^{-2} by improving plant growth, bloom phenology, fruit set, and growth, and thus enhancing yield and fruit production along the year.

In this context, plant growth was higher in the ACC than in the PCC module, particularly in the warm periods of the second year, making clear the benefit of nebulization (Figure 3). A higher rate of photosynthesis of plants grown under the more favorable conditions could explain higher growth and better fruit set [16]. The positive effects of ACC on trunk thickening (Figure 4) predicted a higher yield in this environment, since plants with a thicker trunk bear a greater number of heavier fruits. Several authors have found a high positive correlation between trunk diameter and papaya yields per plant (r = 0.84) [17]. Likewise, the acceleration of plant development achieved in ACC also led to a lower distance from first fruits to ground than in PCC (Table 1). This aspect is very important, because it indicates not only a more rapid abandonment of the vegetative phase and earlier yielding under ACC, but also a larger portion of the plant stem being productive before reaching the ceiling of the greenhouse. Permanhane et al. (2018) [18] found an obvious positive relationship between yield and fruit per plant, but also a positive relationship between yield and trunk diameter, as well as with a lower insertion of flowers and fruits in the trunk and with canopy size in papaya, which was also observed in this experiment.

ACC largely increased total and commercial yields, due to more than double the amount of fruit that were also heavier (Table 2). The benefits observed at harvest were also a consequence of an improvement in flowering. More elongata hermaphrodite flowers were formed under ACC (Figure 5). Differences between both environments were more pronounced in winter and spring, highlighting the beneficial effects of heating. Larger elongate flowers also produce heavier fruits [19]. More male flowers were observed in summer due to the high temperatures (Figure 5). However, nebulization also improved conditions in the ACC module during summer (Figures 1 and 2).

An uninterrupted production of papaya throughout the year facilitates marketing and sale programs. Moreover, producing papayas when the supply is low influences the price which should be higher. Our results showed that ACC increased not only total and commercial yield but also favored fruit production along the year (Figure 6), a consequence of the greater frequency of elongata flowers for a longer time and hence a greater number of commercial fruits making ACC an option to guarantee papaya supply to the market for a longer period. Our results also confirm that active climate control allows one to act on the main determinants of yields [20], obtaining yields exceeding that expected for “Siluet” (80-100 t ha^{-1}) [21].

Differences in fruit size again showed the beneficial effect of ACC, but also the influence of the harvest date, obtaining larger fruit in spring and smaller in summer. The differences in fruit length and equatorial diameter reproduced the variability found in flowers, producing slight variations in the shape of fruits. Fruit sweetness was more influenced by the season the fruit developed than by the climate control strategy established. Our results suggest that temperatures during ripening may not be the main limiting factor for TSS content, with other factors being more important, such as radiation in winter, source–sink relationship [22,23], and photosynthetic capacity of the canopy under plastic [4].

In spite of the greater cultivation costs derived of the equipment and energy, profits are expected to be much higher for ACC in most commercialization scenarios. The profits obtained, when compared to the expenses associated with the equipment and energy, showed that ACC is a profitable strategy for papaya cultivation in the greenhouses in southeast Spain if similar yields to ours are obtained. Only when papaya selling prices fall below EUR 0.90 kg^{-1} does ACC becomes questionable.

5. Conclusions

Our results show the positive effects of active climate control on plant growth, blooming, fruit set, and size, leading to heavier and better yields and to an earlier entry into production of plants under ACC. This was possible because ACC permits more and heavier fruits that were formed earlier, at a lower height of the trunk, and for a more prolonged period. The beneficial effects of cooling and heating were clear, with remarkable increases in commercial yield at affordable costs. Finally, the profitability analyses suggest that higher costs in ACC are more than compensated if good productivity is achieved and likely scenarios of selling prices above EUR 0.90 kg^{-1} occur.

Author Contributions: Conceptualization, J.C. and J.J.H.; methodology, J.J.H.; investigation, I.S.; formal analysis, I.S.; writing—original draft preparation, I.S.; writing—review and editing, J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on requests to authors.

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

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