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Yellow Pitahaya (*Selenicereus megalanthus* Haw.) Growth and Ripening as Affected by Preharvest Elicitors (Salicylic Acid, Methyl Salicylate, Methyl Jasmonate, and Oxalic Acid): Enhancement of Yield, and Quality at Harvest

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Abstract: Yellow pitahaya (*Selenicereus megalanthus* Haw.) is an exotic fruit with great potential for exportation in Ecuador. The research was carried out with the objective of evaluating the fruit growth and ripening as affected by four elicitors: salicylic acid (SA), methyl salicylate (MeSa), methyl jasmonate (MeJa), and oxalic acid (OA), all of them at 1, 5, and 10 mM concentration, compared with untreated plants (control). For each elicitor, nine plants were selected, and on each plant, three fruits were marked to follow up the growth by measuring polar and equatorial diameters. At harvest, yield (kg plant^{-1} and number of fruits plant^{-1}), fruit weight, percentage of pulp and skin, total soluble solids (TSS), titratable acidity (TA), and firmness were determined. Treated plants enhanced fruit size, crop yield, and fruit weight compared with control fruits, although results depended on the elicitor tested and applied doses. The highest and lowest TSS were found in 10 mM MeSa and 5 mM MeJa-treated fruit, respectively, while the highest TA content was shown in 5 mM SA. Firmness was only enhanced in MeJa-treated fruits. Overall, results suggest that preharvest use of elicitors could modulate the pitahaya ripening and could improve quality attributes at harvest.

Keywords: methyl salicylate; salicylic acid; methyl jasmonate; oxalic acid; crop yield; total soluble solid; total acidity; firmness

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1. Introduction

The pitahaya (*Selenicereus* sp.) belongs to the *Cactaceae* family and is an exotic fruit native to Central and parts of South America. It was discovered by the Spanish conquerors, who gave it the name pitahaya, which means scaly fruit. The pitahaya market size is estimated at USD 14.73 billion in 2024 and is expected to reach USD 18.27 billion by 2029, growing at a CAGR of 4.40%. It is widely cultivated in South East Asia, South America, Mexico, USA, and Spain. In recent years, yellow pitahaya (*Selenicereus megalanthus* Haw.) is gaining popularity in international markets. In Ecuador, there are two ecotypes of yellow pitahaya: the first called "Pichincha" (also known as "Nacional") with fruits being reached up to 150 g in weight, and the second known as "Palora" with higher weight (up to 350 g), which is cultivated in large areas of the Palora Cantón in Morona Santiago [1]. According to the Ministry of Agriculture and Livestock [2], Ecuador has approximately 7500 hectares of pitahaya (with an average yield of 7.6 t ha), the Palora being the main yellow-pitahaya-producing areas covering around 2400 ha. The plants are hemiepiphytic and absorb water both through the roots of the soil and through adventitious roots that are developed along the stem or pods, these roots being characteristic of Cactus species [3].

The pitahaya phenology depends on climatic conditions, including photoperiod, precipitation, solar radiation, day and night temperature, among others. Generally, there are 4–7 flowering cycles in a period of 8 months [4]. Accordingly, within a plant, several phases of development can exist such as mature fruits, flowers (buds open and in anthesis), or developing fruits [5]. In addition, the high temperatures during the summer inhibit the pitahaya flowering [6]. The fruit is a medium-sized berry with a yellow skin having nibs and thorns that detach during the ripening process. The pitahaya flesh is white, sweet, soft, and slightly fibrous, containing many small digestible black seeds [7]. The consumption of yellow pitahaya has increased in recent years due to its nutritional content, the pulp being considered as a functional food with medicinal properties [8] due to a high content of polyphenols, carotenoids (β-carotene and lycopene), and rich in vitamins [9].

In modern horticulture, research is focusing on finding preharvest treatments with elicitors, which are naturally occurring compounds, generally recognized as safe (GRAS), having a role on improving crop yield, and enhancing the fruit quality at harvest and during postharvest storage in several fruit and vegetables [10,11]. Some of these elicitors include salicylic acid (SA), methyl salicylate (MeSa), methyl jasmonate (MeJa), and oxalic acid (OA). These elicitors play important roles in plant development, fruit growth and ripening, mainly as inducers of defence mechanisms against pathogens and abiotic stresses. SA and its derivative MeSa modulate some physiological processes related to fruit quality by inducing metabolic and physiological reactions with a great potential for reducing the crop productivity [12]. In sweet cherry, preharvest spraying with SA and MeSa increased total soluble solids (TSS), titratable acidity (TA), and fruit firmness at harvest [13,14]. In table grapes, SA, MeSa, and MeJa applied at 5 and 10 mm delayed berry ripening and lowered crop yield, while ripening was accelerated and yield was enhanced at lower concentrations [15,16]. In pomegranate fruit, MeJa treatments (1, 5, and 10 mM) increased the crop yield, and again MeJa at 1 and 5 mM accelerated the on-tree ripening process, while it was delayed with 10 mM [17]. Oxalic acid is a naturally organic acid occurring in plant tissues, and in the case of fruits, OA has induced clear benefits on delaying senescence and maintaining the quality of sweet cherries [18] and pomegranates [19].

Contrarily to red pitahaya (*Hylocereus* sp.) [20], the growth and ripening of yellow pitahaya and its effect on quality traits are relatively unknown, despite external colour, TSS, and TA, which are considered good indicators of maturity. However, the determination of the period at which the fruit reaches the physiological ripening is essential to obtain superior pitahayas with the highest quality attributes. In addition, to achieve shipments to such remote distances from the place of origin, it is necessary that the pitahaya has a sufficient shelf life during postharvest storage. As far as we know, there is no literature on the use of elicitors on pitahaya yield and quality. Thus, the aim of this work was to study the preharvest application of SA, MeSa, MeJa, or OA on crop yield, physico-chemical properties of pitahaya fruit at harvest, and the effects of these treatments on the fruit maturation process.

2. Materials and Methods

2.1. Plant Material, Treatments, and Experimental Design

The research was carried out in an established crop of yellow pitahaya (*Selenicereus megalanthus* Haw.) under a greenhouse at the Algro Farm, located in the Cantón Palora, Province of Morona Santiago (Ecuador). The Algro Farm has an area of 2.5 ha with 1200 plants of 3 years old, at the geographic coordinates 1°41′00″ South Latitude, 77°58′56.8″ West Longitude, at a height of 839 m. The climate is humid tropical, with relative humidity above 80%, and temperature fluctuates between 18 and 23 °C. For the present investigation, a bifactorial randomized complete block design (4 treatments and 3 concentrations) was used, executing 3 repetitions (n = 3) (Figure S1). A total number of 117 plants were chosen, from which 3 yellow pitahaya plants were selected per block and 3 fruits per plant were marked (9 fruits for each block) to measure fruit growth (total number of fruits was 27).

Treatments were applied with a frequency of 15 days, starting at 55 days after full blossom (DAFB), and after 70, 85, and 100 DAFB, while harvest was carried out at 110 DAFB. The elicitors were methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), and oxalic acid (OA) at concentrations of 1, 5, and 10 mM, while untreated plants served as the control. These doses were based on previous reports with non-climacteric fruits, such as table grapes and pomegranates [15,16,19]. Treatments were performed by spraying 1.5 L per plant of freshly prepared solutions of MeSa, SA, MeJa, and OA (purchased from Sigma-Aldrich, Madrid, Spain) containing 0.5% Tween-20 as surfactant. Treatments were applied early in the morning and under favourable weather conditions (no rain or wind were forecasted).

Pitahaya fruits were manually harvested at the commercial ripening stage based on fruit size, fruit weight (≈360 g), colour (light-green or yellow with green bracts), and the content of total soluble solids (TSS) over 15 °Brix [21]. In addition, the thorns were manually removed with a brush. For each treatment, 27 fruits (9 fruits per replicate) were picked and transferred to the laboratory for further analytical determinations.

2.2. Measurement of Fruit Growth, Crop Yield, Fruit Weight, Pulp, and Skin Percentage

Pitahaya fruit growth was followed by measuring 2 diameters (polar and equatorial) with a digital calliper in the marked fruits every 15 days, and results were expressed in mm ± SE. Pitahaya production was evaluated based on the total yield (kg plant^{-1}) and the number of fruits per plant. Each fruit from control and treated plants were weighed and results were expressed as g ± SE.

2.3. Measurement of Quality Traits

The following quality parameters were measured in control and treated-fruits (9 fruits per replicate) according to previous reports [13,19]: firmness, percentage of skin and flesh, total soluble solids (TSS), titratable acidity (TA), and TSS/TA ratio. Fruit firmness (mean ± SE) was determined in in each fruit by using a GY-3™ penetrometer with a 7.8 mm insertion tip, and results were expressed as kg cm^{-2}.

For each individual fruit, pulp and skin were weighed and results were expressed as percentage ± SE. Then, pulp from the 9 fruits of each replicate was combined to obtain a homogeneous sample, in which TSS and TA were measured in duplicate. TSS were determined as °Brix (mean ± SE), with a Kem brand refractometer, model RA-620, after fruit pulp was extracted. The percentage of TA (mean ± SE) was evaluated by mixing 10 g of pulp and 100 mL of distilled water, which was liquefied until a homogeneous solution, filtered, adding 3 drops of 1% phenolphthalein, and neutralized by using 0.1 N sodium hydroxide until the colour change occurred. Ripening index was calculated as the ratio of TSS/TA.

2.4. Statistical Analysis

A one-way analysis of variance (ANOVA) was performed with data from analytical determinations for each elicitor by using the SPSS software package v. 12.0 for Windows. Mean comparisons were performed using Tukey's test to examine if differences were significant at $p < 0.\ 05$ (Table S1).

3. Results

3.1. Fruit Growth, Crop Yield, and Fruit Weight Subsection

Pitahaya fruit growth was evaluated by measuring the polar (longitudinal) diameter (Figure 1) and the equatorial diameter (Figure 2). For both, a simple sigmoid curve was obtained with a progressive increase in both diameters, although the magnitude was affected by type of elicitor and applied doses.

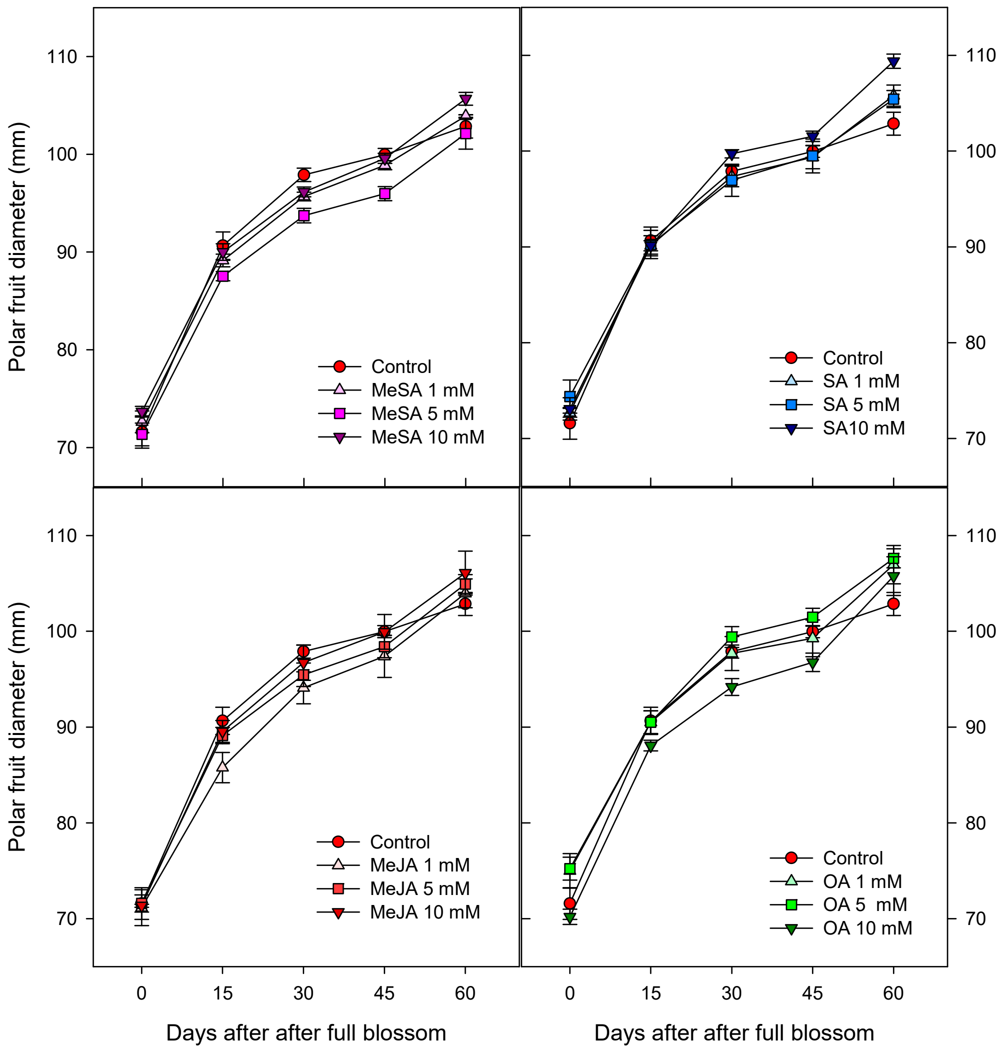

Figure 1. Polar diameter (mm) during growth and ripening of pitahayas from control and treated plants with methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), and oxalic acid (OA) at concentrations of 1, 5, and 10 mM. Data are the mean ± SE (n = 9).

Pitahaya fruit growth and development took approximately 125 days from full blooming to fruit ripening. For control fruits, the maximum polar diameter was significantly lower (≈102 mm) in respect to treated pitahaya, especially with MeSa at 10 mM (≈105 mm), SA at 10 mM (≈109 mm), MeJa at 10 mM (≈106 mm), and OA at 5 mM (≈107 mm). The lowest equatorial diameter was found in control pitahaya (≈75 mm) and significantly higher in treated-fruits, especially for MeSa at 1 mM (≈78 mm), SA at 1 mM (≈82 mm), MeJa at 1 mM (≈79 mm), and OA at 1 mM (≈79 mm).

Crop yield was determined by fruit production (kg plant^{-1}) (Figure 3) and the number of fruits plant^{-1} (Figure 4). The lowest yield was found in SA at 10 mM (≈7 kg plant^{-1}) followed by control pitahaya (≈13 kg plant^{-1}), while the highest was obtained for MeJa at 10 mM (≈20 kg plant^{-1}) followed by OA at 10 mM (≈19 kg plant^{-1}) and MeSa at 5 mM (≈17 kg plant^{-1}). With respect to the number of fruits, SA at 5 or 10 mM showed the lowest yield (≈19 and 30 fruits plant^{-1}, respectively) followed by control (≈42 fruits plant^{-1}), while the highest yield was obtained for MeJa at 5 mM (≈57 fruits plant^{-1}). Fruit weight was significantly affected by treatment (Figure 5), with control fruits being found as the smallest pitahayas (≈294 g), while fruit weight was significantly greater in treated plants. The most effective treatment on enhancing fruit weight was OA at 5 mM (≈388 g) followed by SA at 5 mM (≈377 g), MeJa at 1 mM (≈366 g), and MeSa at 1 mM (≈361 g).

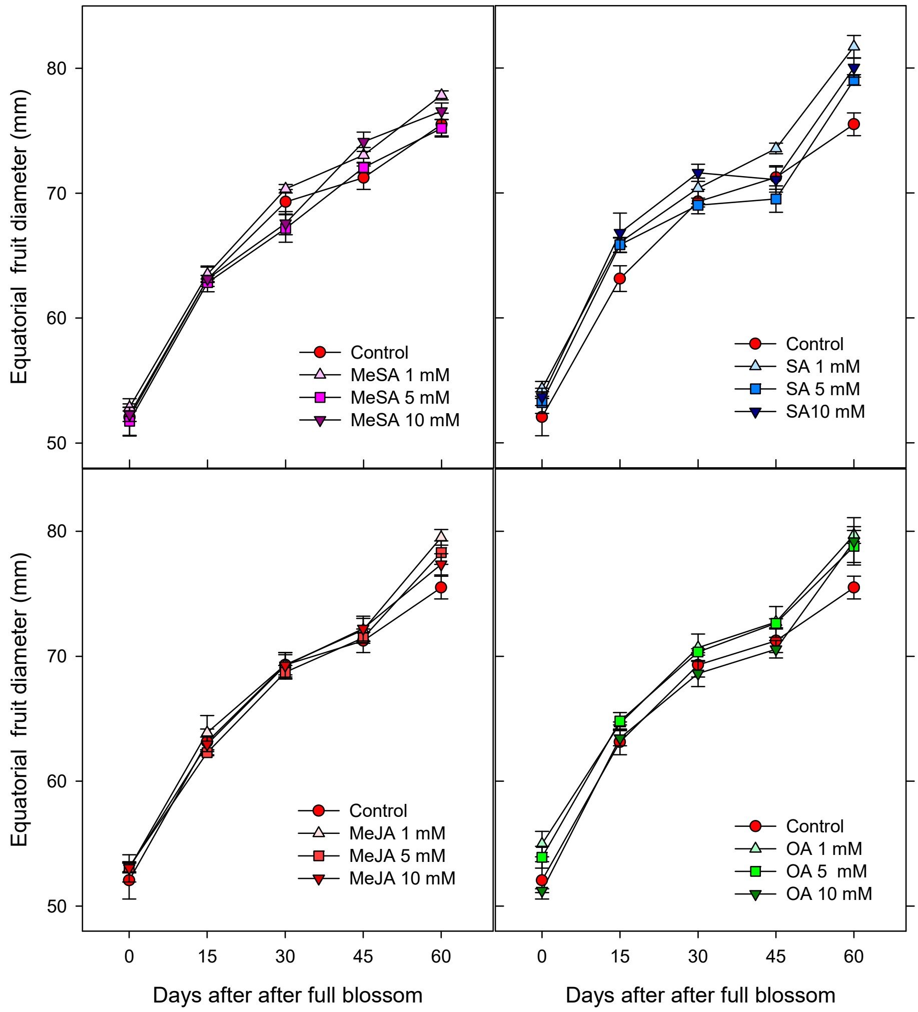

Figure 2. Equatorial diameter (mm) during growth and ripening of pitahayas from control and treated plants with methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), and oxalic acid (OA) at concentrations of 1, 5, and 10 mM. Data are the mean ± SE (n = 9).

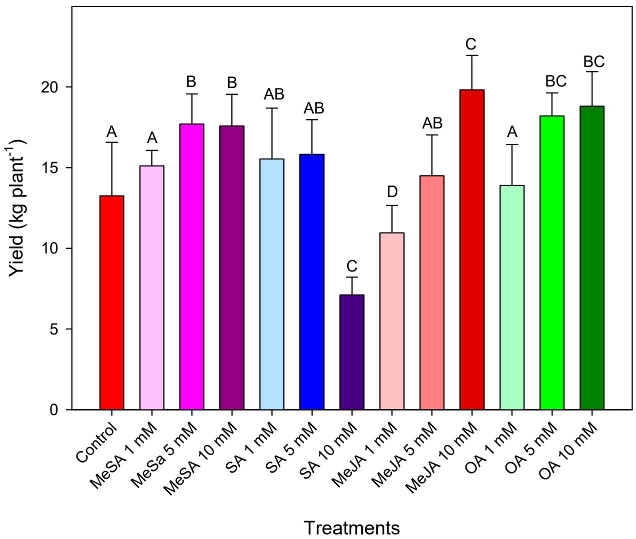

Figure 3. Crop yield (kg plant^{-1}) at harvest time of pitahayas from control and treated plants with methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), and oxalic acid (OA) at concentrations of 1, 5, and 10 mM. Data are the mean ± SE (n = 9). Bars with different letters denote significant differences at $p < 0.05$ after the Tukey's test.

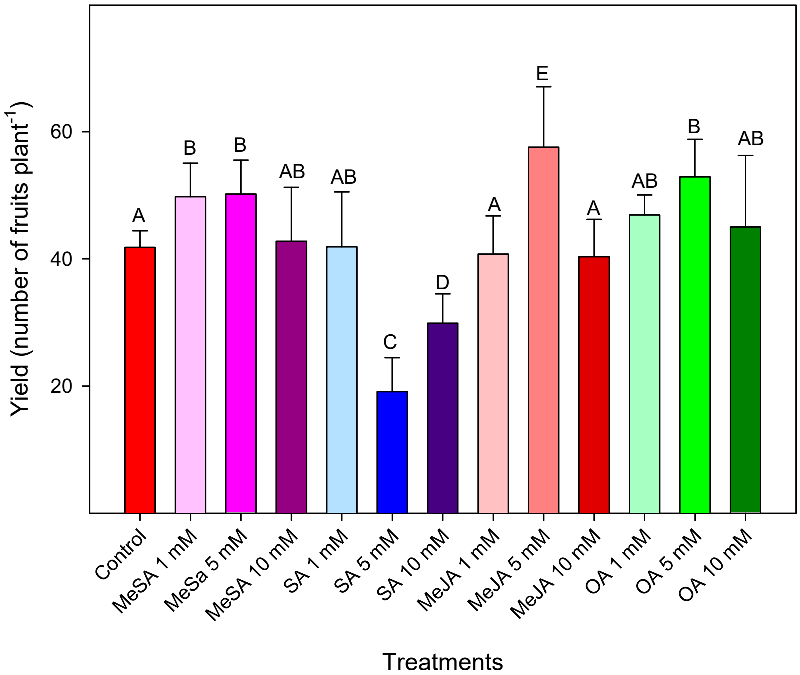

Figure 4. Crop yield (number of fruits plant^{-1}) at harvest time of pitahayas from control and treated with methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), and oxalic acid (OA) at concentrations of 1, 5, and 10 mM. Data are the mean ± SE (n = 9). Bars with different letters denote significant differences at $p < 0.05$ after the Tukey's test.

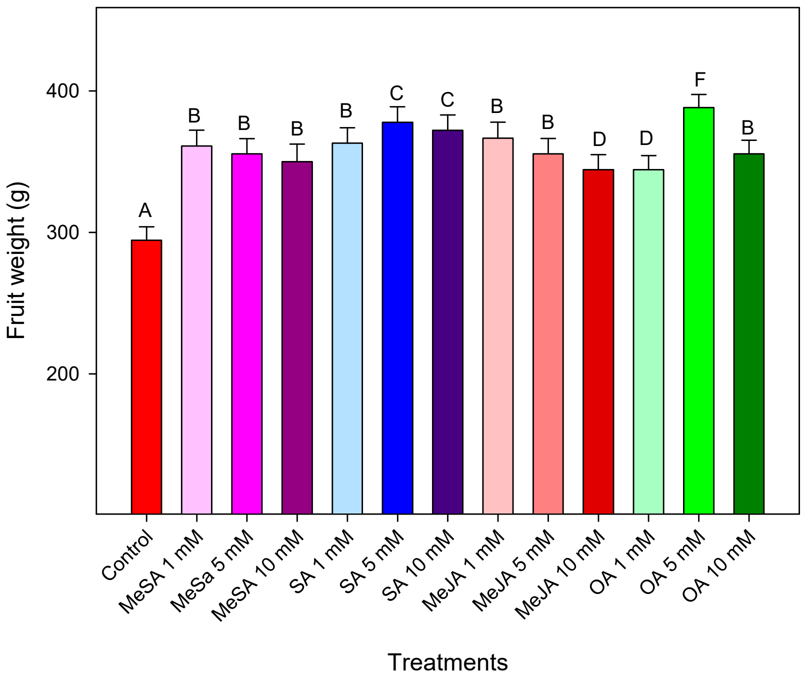

Figure 5. Fruit weight (g) at harvest time of pitahayas from control and treated with methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), and oxalic acid (OA) at concentrations of 1, 5, and 10 mM. Data are the mean ± SE (n = 9). Bars with different letters denote significant differences at $p < 0.05$ after the Tukey's test.

3.2. Quality Parameters: Pulp and Skin Percentage, Fruit Firmness, TSS, and TA

With respect to the percentages of pulp and skin (Table 1), control fruits had 49 and 51%, respectively. All treatments were effective in increasing the pulp content, with the exception of SA at 10 mM, which showed the lowest and the highest pulp and skin, 47 and 53%, respectively. The most important parameters for pitahaya quality are firmness, TSS, and TA. The level of firmness in control fruits was 7.60 ± 0.3 kg cm^{-2}, and the effect of the preharvest treatments was different depending on the elicitor and the applied concentration (Table 1). Thus, MeSa at 5 mM and OA at 1 mM showed lower values of pitahaya firmness (6.60–6.70 kg cm^{-2}), while the only treatment that increased the firmness at harvest was MeJa at 10 mM (10.16 ± 0.7 kg cm^{-2}).

Table 1. Percentage of pulp and skin, total soluble solids (TTS), total acidity (TA), TSS/TA ratio, and firmness of pitahayas harvested from the control plants or plants treated with methyl salicylate (MeSa), salicylic acid (SA), methyl jasmonate (MeJa), or oxalic acid (OA) at concentrations of 1, 5, and 10 mM. Data are the mean ± SE (n = 9). Bars with different letters denote significant differences at $p < 0.05$ after the Tukey's test *.

Treatments	Pulp (%)	Skin (%)	TSS (°Brix)	TA (%)	TSS/TA	Firmness (kg cm^{-2})
Control	48.78 ± 0.9 a	51.21 ± 0.6 a	12.59 ± 0.2 a	1.47 ± 0.3 a	8.56 ± 0.3 a	7.60 ± 0.3 a
MeSa 1 mM	58.54 ± 1.2 b	41.15 ± 0.8 b	13.08 ± 0.2 a	1.53 ± 0.3 a	8.54 ± 0.2 a	8.03 ± 0.5 a
MeSa 5 mM	55.41 ± 0.9 c	44.56 ± 0.9 c	10.87 ± 0.2 b	1.47 ± 0.2 a	7.39 ± 0.2 a	6.60 ± 0.3 b
MeSa 10 mM	54.51 ± 1.1 c	45.49 ± 1.1 c	15.21 ± 0.4 c	1.53 ± 0.3 a	9.94 ± 0.3 b	7.66 ± 0.3 a
SA 1 mM	51.38 ± 1.3 a	48.60 ± 0.8 d	13.73 ± 0.3 a	1.83 ± 0.3 b	7.50 ± 0.3 a	7.76 ± 0.4 a
SA 5 mM	55.68 ± 1.2 c	44.31 ± 1.1 c	12.88 ± 0.2 a	1.90 ± 0.2 b	6.77 ± 0.2 a	8.43 ± 0.4 a
SA 10 mM	46.67 ± 1.3 a	53.32 ± 0.7 a	14.42 ± 0.3 c	2.20 ± 0.3 b	6.55 ± 0.3 a	7.36 ± 0.5 a
MeJa 1 mM	54.10 ± 1.3 c	45.89 ± 0.8 c	12.61 ± 0.4 a	1.57 ± 0.3 a	8.03 ± 0.3 a	7.73 ± 0.4 a
MeJa 5 mM	54.94 ± 0.8 c	45.05 ± 0.6 c	10.26 ± 0.2 b	1.93 ± 0.2 b	5.31 ± 0.2 a	7.80 ± 0.5 a
MeJa 10 mM	52.35 ± 1.2 a	47.64 ± 0.9 d	12.20 ± 0.3 a	1.13 ± 0.2 a	10.79 ± 0.3 b	10.16 ± 0.7 c
OA 1 mM	55.95 ± 0.9 c	44.14 ± 0.7 c	10.88 ± 0.2 b	1.30 ± 0.3 a	8.36 ± 0.3 a	6.73 ± 0.3 b
OA 5 mM	51.19 ± 1.2 a	48.80 ± 0.8 d	11.87 ± 0.3 a	1.50 ± 0.4 a	7.91 ± 0.3 a	8.20 ± 0.5 a
OA 10 mM	58.92 ± 0.8 b	41.07 ± 0.9 b	11.79 ± 0.4 a	1.30 ± 0.3 a	9.06 ± 0.3 b	7.10 ± 0.6 a

* For each quality parameter, different letters within the column denote significant differences at $p < 0.05$ among treatments.

Total soluble solids, expressed as °Brix, was different depending on elicitor type and the applied dose (Table 1). The highest TSS was found in 10 mM SA- and MeSa-treated pitahayas (≈15 °Brix), while the lowest content was observed in 5 mM MeSa- and MeJa-treated fruits (≈10 °Brix) and OA at 1 mM compared to the values in controls (≈12 °Brix). In relation to TA, the application of SA at the three concentrations, as well as MeJa at 5 mM, enhanced the TA with respect to control pitahayas, the values being similar to the MeSA- and OA-treated fruits independently of the applied doses. The lowest ripening index (RI, TSS/TA ratio) was shown for all SA treatments and MeJa at 5 mM (Table 1), while the highest one was observed in pitahayas treated with the maximum concentration tested (10 mM) of MeSa, MeJa, and SA.

4. Discussion

The harvest time of a fruit greatly affects the final quality based on the sugar and acidity content, uniform colour, texture, flavour, and aroma, and all of them depend on the ripening degree [22]. It is generally acceptable that the best quality is reached when the fruit ripens when attached on the plant, but also will influence the further storage. Since only a few studies have been published on the interrelationship between fruit development and quality in pitahaya fruits [5,23], and any reports are available for the use of elicitors and their role in yellow pitahaya growth and ripening, we planned to apply preharvest treatments with SA, MeSa, MeJa, and OA at 1, 5, and 10 mM in order to evaluate the growth, development, and ripening on the plants, focusing on the role of the different elicitors on crop yield performance and the pitahaya quality at harvest.

The pitahaya growth follows a single sigmoid curve, which is typical of non-climacteric fruit, such as pepper, lemon, table grape, or pomegranate, but also in climacteric fruits such as apple and pear, and contrarily to stone fruits which showed a double sigmoid curve [24–26]. The application of the different preharvest elicitors increased pitahaya size with respect to control fruits, with an enhancement in both polar and equatorial diameters. Interestingly, polar diameter was maximum with the highest doses (10 mM) of MeSa, SA, and MeJa, and 5 mM OA, while the equatorial showed the maximum dimensions with the lowest doses (1 mM) of MeSa, SA, MeJa, and OA. The increase in pitahaya size was also accompanied by an enhancement of crop yield in both production (kg plant^{-1}) and number of fruit plant^{-1}. Moreover, all treatments and concentrations were effective in increasing the fruit weight with respect to controls. These effects are attributed to the enhancement of the photosynthetic rate, and thus more assimilates reach the fruit, producing bigger fruits, and also the increase in the number of fruits is attributed to the inhibition of the fruit abscission. Similar results were observed in other fruits, such as sweet cherry, plum, pomegranate, table grape, or tomato, among others [10]. However, these results might be related to the seed development, which should merit further investigation.

The effect of SA application was reported to be dependent on the applied concentration and fruit species. Generally, those fruits with non-edible peel (banana, pineapple, pomegranate, among others, etc.) will tolerate higher concentration in comparison with fruit having edible skin, such as plum, table grape, or cherries [12]. However, there are several situations in which SA at elevated concentrations negatively regulates the fruit development and growth [27], as observed for pitahaya treated with 10 mM SA, for which the lowest yield and number of fruits were obtained, although fruit weight was not negatively affected.

In plum, preharvest treatment with SA and MeSa at 0.5 mM increased fruit weight (≈25%, on average) and total yield (between 10–20%), although the number of fruits per tree was not affected [28]. In pomegranate, SA and MeSa treatments enhanced crop yield, which was attributed to the higher number of fruits per tree, but not to fruit mass [29]. In two sweet cherry cultivars, their fruit volume was higher (≈40%, on average) after preharvest treatment with MeSa at 0.5 and 1 mM, although the yield was not affected [30]. Some explanations could be related to SA ability on increasing the flowering rate, improving fruit set or decreasing fruit abscission. In this study, treatments were applied after fruit set, and thus the higher yield and the number of fruits could be related to lower abscission in comparison with the control pitahaya fruits, since salicylates reduce the normal fruit abscission [31].

It has been observed that MeJa treatments (at 1, 5, and 10 mM) affected the table grape maturation process and crop yield depending on the applied concentration. Therefore, MeJa at 1 mM advanced the berry ripening process (with a higher yield than controls, while a retardation was obtained in treated-pitahayas at 5 and 10 mm a with dose-dependence effect [15]. Lower concentrations of MeJa (at 1, 0.1, and 0.01 mM) confirmed the acceleration of the ripening process, the highest yield being maximum with MeJa at 0.01 mM. On the contrary, MeJa treatments did not affect the fruit mass and size on sweet cherry [32], probably due to that one single treatment performed at the late growth period, specifically before harvest. It is well known that a delay in harvest causes a net increase in fruit weight, as reported for 2 mM MeJa applied to sweet cherry 1 week before harvesting, but failed if applications were made 2 or 3 weeks earlier [33]. In tomato, yield was enhanced after MeJa and SA preharvest treatments, the performance being higher in MeJa-treated plants, which has been attributed to the effect of MeJa on alleviating abiotic stress and is associated with an improvement of the net photosynthesis rate and productivity [34]. In pomegranates, jasmonic acid (JA) enhanced the size and quality traits of 'Wonderful' pomegranate [35], since JA plays essential roles in fruit and growth development [19]. In fact, MeJa at 0.5 mM not only enhanced the bioactive compounds and quality, but also increased the productivity and yield. In 'Mollar de Elche' pomegranate, application of MeJa (at 1, 5, and 10 mM) also increased crop yield, which was attributed to the number of fruits per tree, and it was not related to fruit weight [29]. Similarly, in date fruits, MeJa at 10, 20, and 50 mM showed that the highest yield was obtained for 50 mM, whereas the bunch weight also increased with both 20 and 50 mM [19].

In plum, preharvest application of OA (at 0.5, 1, and 2 mM) induced higher yield in control from the first harvest date, while the contrary occurred in the second one, suggesting that exogenous OA delays on-tree ripening process, although total yield and the number of fruits per tree were always higher in OA-treated trees [36]. Pomegranate trees treated with OA at the same concentrations resulted in higher crop yield due to a higher number of fruits, but with similar fruit weight with no dose-dependence effect [19].

The above elicitors have been proved to induce positive effects in terms of pitahaya crop yield, enhancing the number and weight of the fruits when treatments were applied at preharvest, but this effect was dependent on the type of elicitor and applied concentration. In addition, the percentage of pulp, TSS, TA, and firmness, which are the most important quality attributes in pitahaya, were also affected by preharvest elicitors. In relation to pulp content, all treatments showed higher pulp percentage (50–59%) and lower peel percentage (41–53%), with the exception of SA at 10 mM. These results agree with those reported by Morillo et al. [36] for yellow pitahaya under two productive systems: open field, and under cover.

Total soluble solids, TA, and firmness are important quality attributes for yellow pitahaya and are related to shelf life. TSS was unaffected by preharvest treatments at harvest, although MeSa and MeJa at 5 mM and OA at 1 mM showed a decrease in TSS content compared to control, while MeSa at 10 mM showed the contrary. In sweet cherry, MeSa at 1 or 2 mM also increased TSS and TA concentration [13]. TSS is a significant harvest criterion for pitahaya fruits, and the present results revealed that MeSa at 10 mM advanced the ripening process, while harvest could be delayed with OA at 1 mM and MeJa at 5 mM, in agreement with the results reported in table grape [19] and sweet cherry [37], in which MeJa also showed lower TSS levels than control [32], and was confirmed by the higher TA content of those treated pitahayas. For this parameter, all SA treatments induced a higher percentage of TA, which was unaffected in the remained treated-pitahaya. The application of lower doses of MeJa (0.1 and 0.01 mM) resulted in higher TSS and TA content in table grapes [19]. The highest fruit firmness was obtained for those pitahayas treated with MeJa at 10 mM, while MeSa at 5 mM and OA at 1 mM showed lower valued in firmness compared with control fruits. Accordingly, MeJa was more effective than SA on increasing tomato firmness, probably attributed to the reported role of MeJa on cell-wall metabolism by increasing the activity of the enzymes phenylalanine ammonia-lyase (PAL) and peroxidase (POD) involved on lignin biosynthesis, and thus increasing fruit firmness [34]. OA has been also effective on enhancing fruit firmness in mango [37] and pomegranate [38], mainly due to a decrease in polygalacturonase and pectin methyl esterase enzymes activities, which resulted in a delay of the pectin degradation and rigidification of the cell wall.

In this paper, we report the beneficial effects of the elicitors SA, MeSa, MeJa, and OA in terms of crop performance (higher size, yield, and pitahaya quality). However, these positive effects, attributed to the role of the preharvest application of a particular elicitor at a given dose, cannot rule out the signalling crosstalk with other plant hormones or plant growth regulators that may be involved. Today, whether these elicitors modulate the high or low concentration of the plant hormones, their role during growth and ripening of yellow pitahaya are still unknown, although there is evidence in other fruit and vegetables [39]. SA is an essential signalling elicitor participating in plant responses to several type of stresses throughout a wide signalling crosstalk with ethylene, auxins, MeJa, abscisic acid, melatonin, or brassinosteroids [39–41]. The final result is the alleviation of the stress through both biochemical and physiological responses and also by the change in gene expression. In many cases, JA acts in concert with abscisic acid, ethylene, and SA to achieve a balance the fruit growth and the defence mechanisms leading to tree acclimation to the stress [42].

Among these hormones, there is synergism or antagonism depending on the applied concentration and date of application within the fruit growth cycle. However, it seems that all of them induced the antioxidant enzymes to counteract the reactive oxygen species (ROS) and the reactive nitrogen species (RNS). In line with this, in the future, the possible role of the elicitors on the antioxidant enzymes deserves further investigation. In addition, it is necessary to confirm that these elicitors applied at preharvest will have a positive impact during postharvest storage.

5. Conclusions

This is the first report about the preharvest application of methyl salicylate, salicylic acid, methyl jasmonate, and oxalic acid as elicitors in pitahaya throughout its growth and developmental cycle. These elicitors induced benefits on pitahaya crop production, but the effect depended on the concentration tested. All elicitors increased pitahaya size in both polar (at higher doses, 10 mM) and equatorial (at lower doses, 1 mM) diameters, and fruit weight with the highest fruit mass being found with oxalic acid at 5 mM. Pitahaya yield was also enhanced, the methyl jasmonate at 10 mM being the most effective treatment (≈20 kg plant^{-1}) followed by oxalic acid at 10 mM (≈19 kg plant^{-1}). This enhancement on crop yield was due to higher number of fruits, especially with methyl jasmonate at 5 mM (≈57 fruits plant^{-1}). On the other hand, preharvest elicitors were effective on improving pitahaya quality attributes. A higher pulp percentage was achieved in treated fruits, which was of the great interest in the juice extraction industry. The elicitors also possess the ability to modulate the pitahaya ripening without imparting negative effects on total soluble solids, total acidity, or firmness. Thus, methyl salicylate at 10 mM advanced the pitahaya ripening process, while methyl jasmonate at 5 mM and oxalic acid at 1 mM delayed it. Overall, preharvest treatments with methyl salicylate, salicylic acid, methyl jasmonate, and oxalic acid could be a promising and innovative tool to enhance pitahaya crop yield by obtaining fruits with higher size and weight and improve its quality traits at harvest. In the future, the effect of the elicitors on the yellow pitahaya during postharvest storage under low temperatures to determine the postharvest shelf-life should be investigated.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae10050493/s1, Figure S1: Experimental design with distribution of treatments at random in 3 blocks for pitahaya preharvest elicitors; Table S1: Results from the statistical analysis.

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