horticulturae

Article

On-Farm Supplemental Irrigation of 'Roja Lisa' Cactus Pear: Pre- and Postharvest Effects

Valentín Melero-Meraz [1], Jorge A. Zegbe [1,*], Mayra Denise Herrera [1], Salvado H. Guzmán-Maldonado [2], Guillermo Medina-García [1], Blanca I. Sánchez-Toledano [1], Raquel K. Cruz-Bravo [1] and Miguel Servín-Palestina [1]

1 Campo Experimental Zacatecas, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Km 24.5 Carretera Zacatecas-Fresnillo, Calera de V.R., Zacatecas 98500, Mexico; melero.valentin@inifap.gob.mx (V.M.-M.); herrera.mayra@inifap.gob.mx (M.D.H.); medina.guillermo@inifap.gob.mx (G.M.-G.); sanchez.blanca@inifap.gob.mx (B.I.S.-T.); cruz.raquel@inifap.gob.mx (R.K.C.-B.); servin.miguel@inifap.gob.mx (M.S.-P.)
2 Campo Experimental Bajío, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Km 6.5 Carretera Celaya-San Miguel de Allende, Celaya 38110, Mexico; guzman.horacio@inifap.gob.mx
* Correspondence: zegbe.jorge@inifap.gob.mx

Abstract: *Opuntia* species grow in arid and semiarid lands, where water for irrigation is scarce. However, supplemental irrigation can be a feasible strategy for commercial cactus pear orchards. From 2018 to 2020, a commercial cactus pear orchard was managed to validate the effect of supplemental irrigation on fruit yield, crop water use efficiency, fruit quality, and storability of 'Roja Lisa' cactus pear grown in the semiarid region of Mexico. The irrigation treatments were no irrigation and supplemental irrigation, with four replications. Crop water use was less and, therefore, water productivity greater in non-irrigated plants than in plants with supplemental irrigation. Mean fruit yield, mean fruit mass, and proportion of commercial fruit increased with supplemental irrigation. These differences were more pronounced in growing seasons with less rainfall. Fruit quality at harvest or after room temperature or cold storage was examined. Fruit mass loss rate was reduced in fruit receiving supplemental irrigation in both storage conditions. In addition, supplemental irrigation was consistent with water savings and food security programs in marginal areas: this irrigation strategy improved both pre- and postharvest some quality components of cactus pear fruit. Therefore, this irrigation strategy is suggested for cactus pear growers, depending on the availability of water for irrigation.

Keywords: *Opuntia ficus-indica*; crop water use; fruit quality; fruit yield; storability

Citation: Melero-Meraz, V.; Zegbe, J.A.; Herrera, M.D.; Guzmán-Maldonado, S.H.; Medina-García, G.; Sánchez-Toledano, B.I.; Cruz-Bravo, R.K.; Servín-Palestina, M. On-Farm Supplemental Irrigation of 'Roja Lisa' Cactus Pear: Pre- and Postharvest Effects. *Horticulturae* **2022**, *8*, 483. https://doi.org/10.3390/horticulturae8060483

Academic Editors: Yang Bi, Yongcai Li and Di Gong

Received: 7 May 2022
Accepted: 25 May 2022
Published: 28 May 2022

1. Introduction

Global warming is damaging ecosystems around the world. This is more noticeable in arid and semiarid regions where, now, the temperatures are more extreme, rainfall patterns are changing, soil erosion is increasing, and water scarcity is reflected in poverty and human migration [1]. In addition, water shortage drastically reduces both livestock and agricultural activities in these agricultural lands [2]. However, combining available sustainable technologies and appropriate crops can enhance both crop productivity and grower incomes.

Cactus pear is a succulent, crassulacean acid metabolism plant that is used in semiarid lands to restore degraded lands, as animal fodder, to grow tender cladodes for human consumption [3], for biogas production [4], and as a fruit crop [5,6]. In most producing countries, cactus pear for fruit consumption is cultivated mainly under rainfed conditions. Nevertheless, in some Mediterranean and American countries, this fruit crop is drip-irrigated to increase fruit productivity [5,7–9]. However, groundwater for irrigation is limited in all cactus-pear-growing areas [10], including north-central México, due to the overexploitation of aquifers [11]. Therefore, water conservation and savings, and water productivity enhancement through new irrigation strategies are crucial to both food production and security [12]. Supplemental irrigation may be an alternative for crops cultivated under rainfed conditions [13]. This irrigation strategy has been applied successfully in chickpeas, fava beans, lentils [14], common beans [15], wheat [16], sugarcane [17], sorghum [18], and maize [19]. In all these crops, yield and yield components were significantly improved with supplemental irrigation. In the case of maize, the application of this irrigation technic resulted in economic advantages for growers. Regarding fruit trees, supplemental irrigation also improved yields in peach [13] and olive [20] trees. In the latter fruit crop, water use efficiency was improved without affecting oil content. Unlike the study of Van Der Merwe [21], supplemental irrigation was tested successfully in commercial and non-commercial cactus pear varieties in a semiarid area of north-central Mexico [18]. After three consecutive growing seasons, compared to fully irrigated plants, supplemental irrigation enhanced water use efficiencies and water productivity in favor of water savings by 52%. Cactus pear plants had fruit yields and marketable fruit sizes similar to fully irrigated plants, but some fruit quality parameters were enhanced and the fruit storage life of all cultivars was extended at both room and cold temperatures, which is important for transportation, marketing, and consumers [22].

To our best knowledge, except experimentally, supplemental irrigation has not been tested previously at the level of commercial cactus pear orchards. This study uses a commercial cactus pear orchard to validate the effects of supplemental irrigation on the fruit yield, crop water use, fruit quality, and storability of 'Roja Lisa' cactus pear grown in a semiarid region, where weather conditions are more extreme than the places where previous trials on supplemental irrigation were performed [22]. Therefore, we hypothesize that this irrigation strategy can be replicated at a commercial scale, with similar effects to those reported previously [22,23].

2. Materials and Methods

2.1. Experimental Site, Vegetative Material, and Orchard Management

The experiment was conducted in a commercial cactus pear orchard located in 'La Victoria', Pinos, Zacatecas, Mexico (lat. 22°22′ N, long. 101°67′ W, elevation 2161 m) from 2018 to 2020. Fifteen-year-old cactus pear plants of the cultivar 'Roja Lisa' (*O. ficus-indica* (L.) Mill.) were used. This cultivar can be used as fodder, vegetable (tender cladodes), and fruit. This essay is oriented to its consumption as fresh fruit. The fruit peel and pulp are red, medium size (8.5 and 5.7 cm of equatorial and polar diameters, respectively), fruit mass (136 g; 60% pulp and 40% peel) that has juicy pulp with 14.5° Brix of sugar content at the ready-to-eat stage. The plants were trained to an in-row-oriented system and spaced at 5.6×2.7 m between rows and plants, respectively. The orchard's management program included cladode pruning, fruit thinning, drip irrigation, mineral and organic fertilization, and weed and pest control, as required.

2.2. Treatments and Experimental Design

The field experiment had two irrigation treatments: no irrigation (NI, as control) and supplemental irrigation (SI). A section of the orchard was drip-irrigated three times during each dry season (April–June) of the 2018 and 2019 growing seasons and just once in 2020 due to malfunctioning of the irrigation pumping system. The irrigation was applied according to the grower's criterion; nevertheless, the irrigation water applied was calculated using three-quarters of the plant area, and volume was estimated as the product of the number of drippers, dripper flow rate (4 L h^{-1}), and time used for each irrigation event. Irrigation water applied was calculated by adding all irrigation events. The physical soil parameters for permanent wilting point and field capacity were established at 0.14 and 0.27 cm^3 cm^{-3}, respectively. From bloom until harvest, soil water content (θ) was monitored in both treatments using time-domain reflectometry (TDR, Mini-Trase System, Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Probes were placed 20 cm deep in the soil at 10 and 70 cm from emitters and plants, respectively. Climate information was recorded by an automated weather station placed 600 m from the experiment. This information, in part, was used to estimate the reference evapotranspiration by the Penman–Monteith method [9] and to track air temperature and precipitation (Figure 1). The year 2019 was the driest growing season. The experiment was conducted in a completely random design with four replicates, each comprising two uniform plants whose crop load was adjusted by fruit thinning [24] to minimize, in part, the variation among replicates. One plant was used for destructive sampling, while the other one was used to assess fruit yield, fruit sizing distribution, fruit quality, and storability.

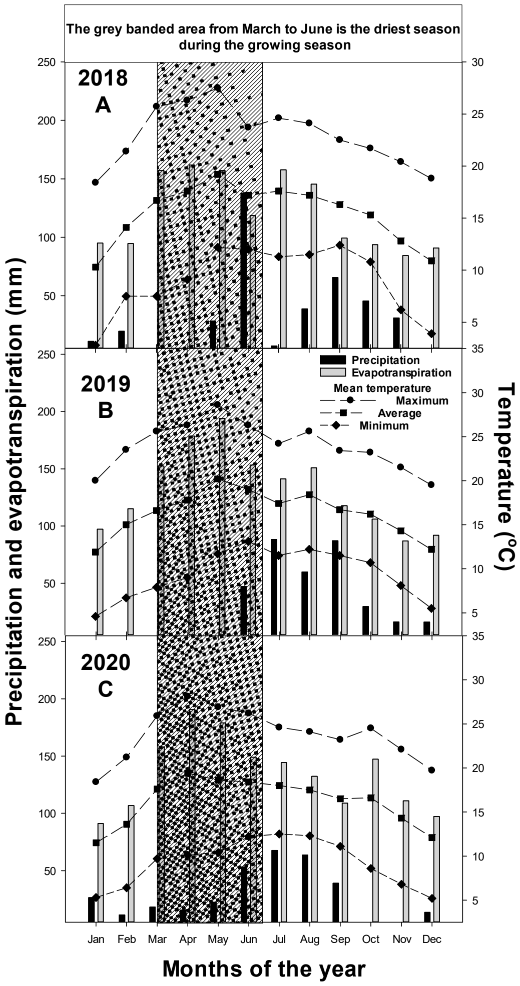

Figure 1. Climate conditions prevailed at the experimental site from 2018 to 2020. La Victoria, Pinos, Zacatecas, México.

2.3. *Preharvest Determinations*

2.3.1. Relative Water Content (RWC)

RWC was determined from two fruiting cladodes per replication as follows: between 12:00 and 13:00 h on every sampling date, two stem segments were taken out with a cork borer (17 mm internal diameter). The tissue samples were placed and sealed in Eppendorf tubes. The tissue specimens were individually weighed to determine the fresh mass (FM), turgid mass (TM), and dry mass (DM). The tissue samples were placed into the Eppendorf tubes and hydrated to full turgidity for 3 h to determine TM. DM was determined by oven-drying the samples at 65 °C to constant mass. RWC was calculated as RWC (%) = ((FM − DM)/(TM − DM)) × 100.

2.3.2. Crop Production

Cactus pear productivity was measured as fruit yield, mean fruit mass, and fruit size distribution. The harvest took place from June 28 to August 30 in 2018, from Jun 26 to August 5 in 2019, and from July 13 to August 4 in 2020 when the fruit peel color was reddish-green. Fruit from each plant was harvested separately and graded from Grade 1 to Grade 4 using the equatorial diameter (cm). Grade 1 fruit had a diameter between 6.0 and 7.0 cm. The corresponding values for Grade 2, Grade 3, and Grade 4 were 5.0 to 5.9 cm, 4.0 to 4.9 cm, and shorter than 4.0 cm, respectively. Fruit from each plant was counted and weighed, and the total mass was measured as gross yield. The mean fresh mass of fruit was calculated by dividing the gross yield by the number of fruits per plant. Water productivity was measured here by dividing the gross yield (kg) and commercial fruit yield (fruit of Grade 1 and 2) by the volume of applied irrigation water (m^3).

2.4. Postharvest Determinations

Fruit Quality

To assess the fruit quality (FQ) of the third harvest event, fruit at color break (green to red) was harvested randomly from the outer and middle parts of cactus pear plants. In the postharvest laboratory, three lots each of 24 Grade 1 fruits (6 fruit per replicate per treatment) were formed. One group was used to evaluate FQ at harvest; the other two lots were stored in a cold room or at room temperature. The storage periods ceased when, on average, fruit lost 8% of its original mass, and FQ was measured. The cold room temperature (T) and relative humidity (RH) values ($\pm$ standard deviation) were set at 7 °C and 90 $\pm$ 4%, respectively. At room temperature, T and RH values were 24 $\pm$ 2 °C and 40 $\pm$ 10% in 2018, 25 $\pm$ 2 °C and 37 $\pm$ 7% in 2019, and 25 $\pm$ 2 °C and 38 $\pm$ 7% in 2020. Room T and RH were determined every two hours with a data logger (model 42276, ExTech, Instruments, Waltham, MA, USA). Before storing, the spines were removed from the fruit, and the fruit was treated with a solution of copper sulfate (2.5 mL L^{-1}) and chlorine (1%).

FQ evaluations at harvest or after storage followed the same protocol. The mass of each fruit was recorded with a precision scale (VE-303, Velab, Ciudad de Mexico, Mexico). After removing the fruit skin, two flesh firmness determinations were made on two opposite sides, in the equatorial part of each fruit, using a press-mounted Wagner penetrometer (model FT 327, Wagner Instruments, Greenwich, CT, USA) with an 11.1 mm head. For each flesh firmness determination, some juice drops were mixed and the soluble solids concentration was measured with a digital refractometer with automatic temperature compensation (model PR-32α, Atago, CO., Ltd., Tokyo, Japan). Each fruit was split into peel and pulp, and each tissue was weighed separately with a precision scale (VE-303, Velab, Ciudad de Mexico, Mexico). The dry mass of fruit pulp was determined from 25 g composite samples of fresh pulp tissue (including seeds) from three fruits. Samples were oven-dried at 60 °C for one week to constant mass. Fruit mass loss was evaluated weekly by weighing the fruit individually at both storage conditions, taking into account the initial mass to calculate this parameter.

2.5. Data Analysis

The pre- and postharvest data were analyzed with a completely randomized model using the general linear model procedure of Statistical Analysis System software (SAS Institute ver. 9.4, 2002–2010, Cary, NC, USA). As fruit size distribution was expressed in percentage, it was arcsine-transformed and de-transformed for its presentation. Treatment means were separated by Fisher's least significant difference test at $p \leq 0.05$. Fruit decay incidence was analyzed by the chi-square test.

3. Results

3.1. Preharvest Results

Soil Water Content (θ) and Relative Water Content (RWC)

The θ of plants under no irrigation was below the permanent wilting point (PWP), but when plants received supplemental irrigation plus rainfall, it was between field capacity (FC) and PWP in 2019 and 2020. In contrast, except for one occasion at 204 days in 2019, despite the early rainfall in the 2020 growing season (Figure 1), θ remained below the PWP in non-irrigated plants (Figure 2c,d). The RWC was sensitive to changes in θ in both treatments, but plants under supplemental irrigation had the greatest RWC in both growing seasons (Figure 2a,b). The θ and RWC were not measured in 2018, but it is assumed that they were similar to 2019 and 2020.

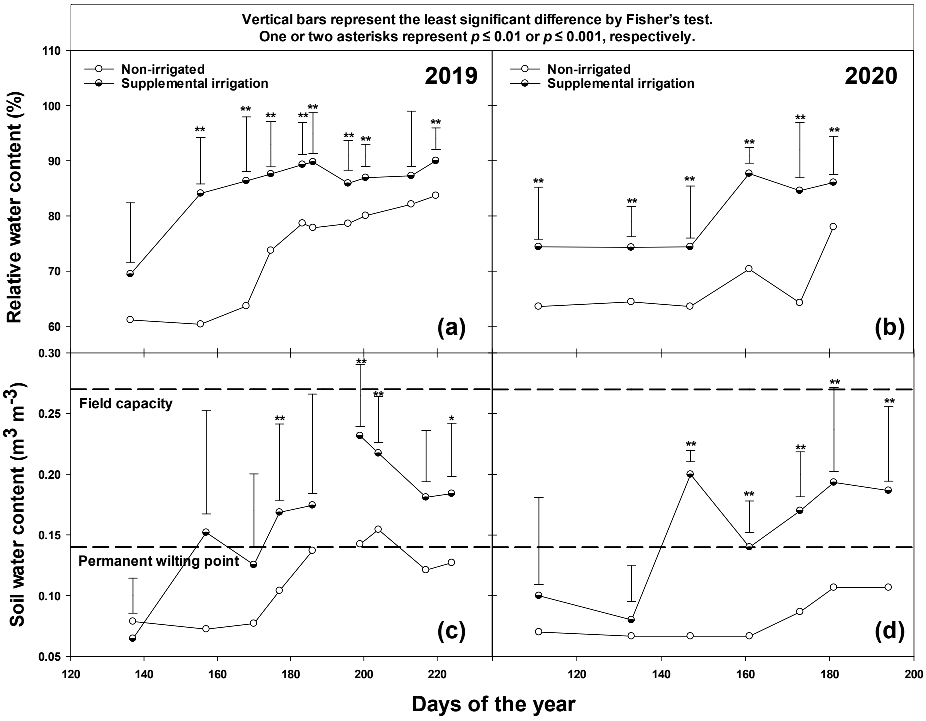

Figure 2. Changes in relative water content of cladodes (**a**,**b**) and soil water content (**c**,**d**) in experimental plots of 'Roja Lisa' cactus pear plants undergoing no irrigation or supplemental irrigation in 2019 and 2020. The data were collected in the commercial orchard 'Las 100 Hectáreas'. La Victoria, Pinos, Zacatecas, Mexico.

Based on the irrigation water applied, crop water uses on the plants given supplemental irrigation was, over a three-year average, 2.5-fold greater than in non-irrigated plants (Table 1). Except for in 2018, this was reflected in increased total fruit yield, commercial fruit yield, and mean mass of fresh fruit of irrigated plants, with a corresponding reduction in water productivity in the first two growing seasons (Table 2). Fruit size distribution was enhanced in plants undergoing supplemental irrigation, particularly in the fruit of the first category (the most marketable fruit) in the second and third growing seasons (Table 3).

Table 1. Accumulated reference evapotranspiration (ETo), irrigation water applied (IWA), and crop water use (CWU) of 'Roja Lisa' cactus pear under non-irrigated and supplemental irrigation in 2018, 2019, and 2020. Data were collected from a commercial orchard, 'Las 100 Hectáreas'. La Victoria, Pinos, Zacatecas, Mexico.

Year/Irrigation Treatment	ETo (mm)	IWA (mm)	CWU (mm)
2018			
Non-irrigated	588	0	155
Supplemental irrigation	588	219	374
2019			
Non-irrigated	657	0	50
Supplemental irrigation	657	247	297
2020			
Non-irrigated	522	0	113
Supplemental irrigation	522	24	137

Table 2. Influence of supplemental irrigation on total fruit yield (TFY), commercial fruit yield (CFY, Grade 1 + Grade 2), and mean mass of fresh fruit (MMFF) and water productivity of 'Roja Lisa' cactus pear. Fruit were harvested from the commercial orchard 'Las 100 Hectáreas'. La Victoria, Pinos, Zacatecas, Mexico.

Year/Irrigation Treatment	TFY (t ha^{-1})	CFY (t ha^{-1})	MMFF (g)	Water Productivity (kg m^{-3})	
				CFY	TFY
2018					
Non-irrigated	17.3a *	14.0a	113.4a	9.1a	11.1a
Supplemental irrigation	18.4a	16.7a	117.7a	4.5b	4.9b
Least significant difference	9.3	9.6	29.6	4.1	3.0
Significance ($p > F$)	0.77	0.52	0.74	0.03	0.002
Coefficient of variation (%)	30.1	36.1	14.8	35.0	21.3
2019					
Non-irrigated	17.7a	13.7b	109.3b	27.4a	35.4a
Supplemental irrigation	32.3a	28.5a	126.9a	9.6b	10.9b
Least significant difference	15.1	14.5	14.3	9.4	10.6
Significance ($p > F$)	0.05	0.05	0.02	0.004	0.001
Coefficient of variation (%)	35.0	39.6	7.0	29.4	26.4
2020					
Non-irrigated	23.8a	19.4b	103.8a	17.2a	21.1a
Supplemental irrigation	29.1a	26.3a	133.0b	19.3a	21.3a
Least significant difference	5.6	5.4	15.3	4.0	4.1
Significance ($p > F$)	0.06	0.02	0.004	0.25	0.93
Coefficient of variation (%)	12.2	13.6	7.5	12.6	11.2

* Within columns per year, means followed by the same letter were not significantly different by Fisher's test at $p \leq 0.05$.

Table 3. Influence of supplemental irrigation on the fruit size distribution of 'Roja Lisa' cactus pear. Fruit were harvested from the commercial orchard 'Las 100 Hectáreas'. La Victoria, Pinos, Zacatecas, Mexico.

	Fruit Size Distribution (%)			
	Grades (Equatorial Diameter, cm)			
Year/Irrigation Treatment	**1 (7.0–6.0)**	**2 (5.9–5.0)**	**3 (4.9–4.0)**	**4 (3.9–3.5)**
2018				
Non-irrigated	24.0a *	56.0a	19.1a	0.9a
Supplemental irrigation	33.4a	57.7a	7.8a	1.11a
Least significant difference	34.3	17.7	21.3	1.6
Significance ($p > F$)	0.53	0.82	0.24	0.72
Coefficient of variation (%)	69.2	18.0	91.5	96.4
2019				
Non-irrigated	7.2b	70.2a	21.7a	0.8a
Supplemental irrigation	22.2a	64.6a	12.9a	0.3a
Least significant difference	9.1	10.2	11.1	1.6
Significance ($p > F$)	0.01	0.23	0.10	0.48
Coefficient of variation (%)	36.0	8.8	37.0	166.7
2020				
Non-irrigated	8.3b	73.1a	17.0a	1.6a
Supplemental irrigation	19.7a	70.7a	9.6b	0.0b
Least significant difference	5.8	5.5	4.5	0.9
Significance ($p > F$)	0.00	0.32	0.01	0.01
Coefficient of variation (%)	23.8	4.4	19.6	69.2

* Within columns per year, means followed by the same letter were not significantly different by Fisher's test at $p \leq 0.05$.

3.2. Postharvest Results

3.2.1. Fruit Quality

At harvest, irrigated plants averaged a more fleshy mass of fruit and its components (peel and pulp) over the three growing seasons, although the differences were not always significant. These results remained consistent after room temperature storage for 13 weeks in 2018 and 9 weeks in 2019 and 2020 and after cold storage for 14, 11, and 10 weeks in 2018, 2019, and 2020, respectively (Table 4).

At harvest, plants under both treatments produced fruit with similar firmness in all years and after storage at either temperature, except in 2019, when fruits from irrigated plants and stored in a cold room were maintained the firmest (Table 5).

In 2018, at harvest, soluble solids concentration showed no measurable differences between non-irrigated and supplementally irrigated fruit. The same was true after fruit storage at room temperature or in a cold room. In contrast, soluble solids concentration was reduced in supplementary irrigated fruit at harvest in 2019 and 2020. This last trend was also consistent after storage at room temperature or in a cold room. The pulp dry matter acted similarly to the soluble solids concentration (Table 5).

Fruit from non-irrigated plants had the fastest fruit mass loss (FML) rate and, therefore, reached the threshold of 8% of the FML rate established for this non-climacteric fruit. Alternatively, fruit deterioration was observed before reaching this threshold. The opposite was observed in supplementally irrigated fruit, which had a long storage life (Figure 3a–c). Similar behavior was observed in fruit stored in a cold room. In both fruit types, the FML rate was lower with cold room storage than at room temperature. Nevertheless, the assay ended before reaching the FML threshold because signs of fruit deterioration were observed (Figure 3d–f). No measurable differences were found in 2020 (Figure 3f).

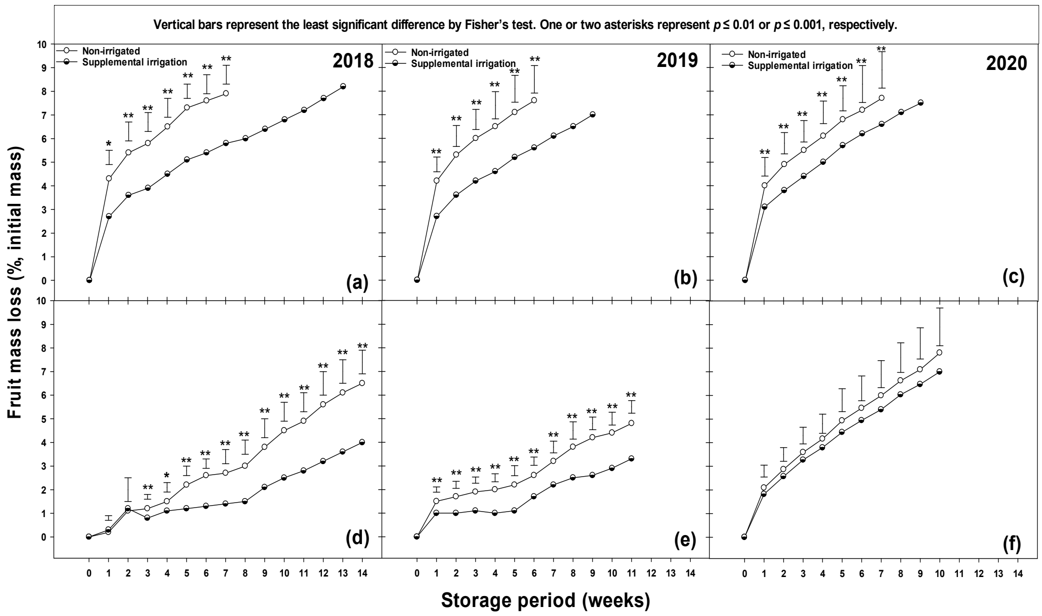

Figure 3. Changes in fruit mass loss of 'Roja Lisa' cactus pear, as influenced by supplemental irrigation in three consecutive growing seasons. Fruit were harvested from the commercial orchard 'Las 100 Hectárias'. La Victoria, Pinos, Zacatecas, Mexico.

Table 4. Influence of supplemental irrigation on fruit mass attributes of 'Roja Lisa' cactus pear. Fruit were harvested from the commercial orchard 'Las 100 Hectárias'. La Victoria, Pinos, Zacatecas, Mexico.

Irrigation/Fruit Condition	Fresh Mass of Fruit (g)			Fresh Mass of Peel (g)			Fresh Mass of Pulp (g)		
	2018	2019	2020	2018	2019	2020	2018	2019	2020
Harvest									
Non-irrigation	122.7b *	114.2b	136.4a	59.6b	52.1b	54.2b	63.1b	63.1a	82.2a
Supplemental irrigation	150.5a	133.7a	160.1a	70.2a	65.6a	73.0a	80.3a	68.2a	87.1a
Least significant difference	14.6	18.4	25.1	5.1	9.8	13.6	11.4	10.4	13.6
Significance ($p > F$)	0.003	0.04	0.06	0.002	0.01	0.02	0.01	0.28	0.41
Coefcient of variation (%)	11.8	7.9	12.7	12.8	8.6	13.6	13.9	11.3	15.5
Room temperature **									
Non-irrigation	116.2b	121.2b	129.6b	41.0b	41.5b	41.6b	75.2a	79.7a	88.0a
Supplemental irrigation	138.8a	143.4a	152.4a	52.8a	55.7a	61.4a	85.9a	87.7a	91.0a
Least significant difference	14.4	15.6	16.0	6.1	6.7	7.5	14.5	14.3	12.6
Significance ($p > F$)	0.007	0.01	0.01	0.002	0.003	0.001	0.125	0.25	0.61
Coefcient of variation (%)	10.3	11.0	10.3	14.1	12.6	13.4	11.7	14.7	13.2
Cold room ***									
Non-irrigation	139.3b	119.1b	126.6b	50.9b	47.6b	41.4b	88.4a	71.4b	84.2a
Supplemental irrigation	168.6a	161.9a	146.7a	65.2a	64.9a	54.9a	103.3a	96.9a	91.8a
Least significant difference	22.7	19.9	12.2	9.4	8.1	5.6	17.7	13.0	8.1
Significance ($p > F$)	0.02	0.001	0.01	0.01	0.002	0.002	0.09	0.003	0.06
Coefcient of variation (%)	8.5	11.4	12.2	11.7	11.7	16.8	8.8	14.1	12.7

* Within columns, per fruit conditions means followed by the same letter were not significantly different by Fisher's test at $p \leq 0.05$. ** Room temperature conditions were set at 24 ± 2 °C and 40 ± 10% in 2018; 25 ± 2 °C and 37 ± 7% in 2019; and 25 ± 2 °C and 38 ± 7% in 2020. *** Cold storage conditions were set at 7 °C and 90 ± 4%.

Table 5. Influence of supplemental irrigation on some fruit quality attributes of 'Roja Lisa' cactus pear. Fruit were harvested from the commercial orchard 'Las 100 Hectárias'. La Victoria, Pinos, Zacatecas, Mexico.

Irrigation/Fruit Condition	Fresh Firmness (Newtons)			Soluble Solids Concentration (Brix)			Dry Mass of Pulp (mg g^{-1} FW)		
	2018	2019	2020	2018	2019	2020	2018	2019	2020
Harvest									
Non-irrigation	34.6a *	28.3a	28.7a	12.0a	13.9a	13.3a	145.8a	219.3a	143.9a
Supplemental irrigation	34.2a	32.5a	28.2a	12.2a	11.9b	12.6a	148.0a	210.4b	131.2a
Least significant difference	4.1	3.8	5.6	0.8	0.08	0.9	6.3	4.1	15.5
Significance ($p > F$)	0.85	0.08	0.86	0.5	0.001	0.11	0.50	0.000	0.09
Coefficient of variation (%)	18.3	14.2	18.1	6.8	6.9	6.8	5.7	1.8	10.9
Room temperature **									
Non-irrigation	22.2a	23.1a	23.5a	11.4a	12.8a	13.3a	139.7a	187.1a	151.1a
Supplemental irrigation	22.3a	22.5a	21.7a	10.8a	11.0b	11.3b	141.4a	173.8b	127.7b
Least significant difference	4.9	3.8	3.7	0.8	0.7	0.4	17.5	5.3	9.5
Significance ($p > F$)	0.99	0.8	0.30	0.07	0.001	0.0001	0.8	0.001	0.001
Coefficient of variation (%)	17.5	18.5	15.3	5.0	6.6	5.6	10.8	3.1	12.3
Cold room ***									
Non-irrigation	33.2a	29.9b	31.7a	11.6a	12.2a	13.6a	129.3a	191.7a	150.9a
Supplemental irrigation	33.6a	33.3a	30.8a	11.4a	11.4b	13.0b	134.3a	187.0a	147.5a
Least significant difference	4.4	2.6	3.1	0.4	0.7	0.5	18.6	12.5	8.9
Significance ($p > F$)	0.85	0.04	0.52	0.60	0.04	0.02	0.54	0.4	0.38
Coefficient of variation (%)	10.6	13.1	10.3	5.6	5.8	8.1	21.7	5.5	10.4

* Within columns per fruit conditions means followed by the same letter were not significantly different by Fisher's test at $p \leq 0.05$. ** Room temperature conditions were 24 ± 2 °C and 40 ± 10% in 2018; 25 ± 2 °C and 37 ± 7% in 2019, and 25 ± 2 °C and 38 ± 7% in 2020. *** Cold storage conditions were set at 7 °C and 90 ± 4%.

3.2.2. Fruit Decay Incidence

The chi-square (χ^2) test of independence concluded that irrigation treatment and storage condition are independent of each other for fruit decay presence (χ^2 = 1.32, p = 0.25; Fisher's exact test p = 0.262). The highest incidence of decay occurred in the fruit from plants given supplemental irrigation that were then stored in the cold room in 2018 or 2019. Decay was minimal or absent in 2020 (Table 6).

Table 6. Number and percentage (in brackets) of fruit with decay from 'Roja Lisa' cactus pear plants under different irrigation treatments and storage conditions in three consecutive growing seasons.

Year/Irrigation Treatments	Storage Conditions	
	Room Temperature	Cold Room
2018		
No irrigation	1 (4.2)	2 (8.3)
Supplemental irrigation	2 (8.3)	4 (16.7)
2019		
No irrigation	2 (8.3)	0 (0)
Supplemental irrigation	2 (8.3)	7 (29.2)
2020		
No irrigation	0 (0)	0 (0)
Supplemental irrigation	1 (4.2)	0 (0)

4. Discussion

Supplemental irrigation could be a feasible alternative to full irrigation to enhance the productivity of cactus pear orchards in semiarid agricultural lands [22,23]. This experiment examined its effect on fruit yield, crop water use, fruit quality, and storability of 'Roja Lisa' cactus pear grown in a commercial orchard in the semiarid region of Mexico.

Similar to other fruit trees [25–27], the relative water content of cactus pear cladodes acted as an indicator of plant water status and was sensitive to changes in soil water content in both irrigation treatments. This occurred due to water inputs (irrigation or rainfall) and created measurable differences between non-irrigated and supplementally irrigated plants (Figures 1 and 2). The permanent wilting point for this kind of soil was established at 0.14 m^3 m^{-3}, but the soil water content in non-irrigated cactus pear plants was as low as 0.06 m^3 m^{-3} in 2020 (Figure 2). However, after rainfall, these plants not only recovered but also produced a commercial yield (Table 2). This shows that the permanent wilting point for this plant must be established because this soil physical parameter is the product of the plant (succulent)–soil–atmosphere continuum [28]. This determination was not made during this study, and it was not the purpose of this study either.

Because non-irrigated plants received water input only from rain, supplementally irrigated plants had greater crop water use and, therefore, lower water productivity than those under no irrigation (Tables 1 and 2). The latter conclusion is supported by previous irrigation research on cactus pear plants that received various irrigation techniques [9], including a comparison of full and supplemental irrigation [22]. Similar results were seen in peach and olive orchards grown under water scarcity [29], similar to the weather conditions of the place where this experiment was conducted. In 2020, water productivity, measured as total fruit yield and commercial fruit yield, was similar between irrigation treatments (Table 2). This was attributed to both treatments receiving a similar amount of water, mainly due to rain (Table 1). The reduced water applied to supplementally irrigated plants was due to the malfunctioning of the irrigation system. However, this season was rainy, which could have masked the effect of both treatments on total fruit yield. This suggests that in a rainy growing season, irrigation may be suspended, at least in succulent plants such as cactus pear [21].

This experiment was expected to enhance cactus pear fruit yield by applying supplemental irrigation in a semiarid region facing water scarcity for agricultural activities. As seen at the start of a mineral fertilization program for this plant species [30], in 2018, the irrigation treatments made no measurable difference to total fruit yield, commercial fruit yield, and mean fruit mass (Table 2). This may be attributed to the plants' adjustment to irrigation [9] because in the two following growing seasons, commercial fruit yield, mean fruit mass, and fruit size distribution were greater in supplementally irrigated plants than in non-irrigated plants. The cladodes of the latter had the lowest relative water content (Figure 2) and a shriveled appearance by the middle of the growing season, indicating a water stress effect. Hence, it is likely that these plants had limited photosynthetic activity and, therefore, a low rate of photo-assimilate remobilization from source tissues into the reproductive sink organs [31]. The data also indicate that in a rainy season, which is atypical in this region, supplemental irrigation must be applied judiciously to produce marketable fruit with lower irrigation costs (Table 3).

The influence of preharvest management on the postharvest quality maintenance and storability of cactus pear fruit has received little attention [23]. We assessed the influence of no irrigation and supplemental irrigation on cactus pear fruit at harvest and their effect on postharvest life during storage at room temperature and in cold storage. Cactus pear plants receiving supplemental irrigation produced fruit with significantly greater fruit and peel mass and occasionally significantly more pulp than cactus pear plants grown without irrigation (Table 4). This suggests that the non-irrigated fruit would have had an insufficient supply of carbohydrates from the source cladodes (leaves as a source were limiting) or that the fruit (sink tissues) was unable to utilize the available carbohydrates from the source cladodes fully (sink-limited) [32]. Except for this measure, irrigation treatments did not affect flesh firmness at harvest or after cold or room temperature storage (Table 5). Although this study did not examine fruits at the cellular level, neither irrigation treatments nor storage conditions modified fruit cell density, as occurred in other fruits [33,34], including fruit from various cactus pear cultivars [23]. The soluble solids concentration and pulp dry matter were usually greater in non-irrigated fruit than in supplementally irrigated fruit, at harvest and after storage at either temperature (Table 5). The reduced soluble solids concentration and dry mass of pulp in irrigated fruit are probably due to dilution. The larger cells of irrigated fruits can store more water than the presumably smaller ones in non-irrigated fruits or under deficit irrigation [9,23,33,34]. The association of fresh mass of fruit with soluble solids concentration (r = −0.18; p = 0.0002) and dry mass of pulp (r = −0.05; p = 0.54) was weak and negative.

A mass loss of 5% causes many perishable commodities to appear wilted and shriveled, among other postharvest physiological disorders [35]. For white cactus pear varieties, an 8% mass loss during storage creates visible changes in fruit appearance (wilting and shriveling) and fruit texture (flaccidity and softening) [36]. In this experiment, supplementally irrigated fruit minimized fruit mass loss rates and prolonged fruit storage life under both storage conditions, as reported previously for cactus pear undergoing deficit irrigation [9] or supplemental irrigation [23]. After harvest, fruit mass loss occurs mainly via transpiration [37,38]. Therefore, supplemental irrigation is likely to promote positive changes at the levels of the epidermis [23,39] that minimize fruit mass loss to the surrounding atmosphere [35]. This finding has important implications for the local and long-distance transportation, marketing, and final consumers of this exotic fruit.

In cactus pear plants, fruit decay incidence depends on the cultivar, fruit maturation stage, and storage conditions. In this experiment, all fruit were collected at the same fruit maturity (color break) and were spineless, curated with a solution of copper sulfate and chlorine, and stored, theoretically, under the same conditions. Temperature variation could be a key factor in postharvest disease occurrence. Cactus pear fruit rot is caused by *Alternaria alternata*, *Chlamydomyces* spp., *Fusarium* spp., *Macrophomina phaseolina*, and *Penicillium polonicum* [40,41]. Although this experiment was not designed to study cactus pear fruit diseases, both storage temperatures and causal agents deserve special attention in order to minimize fruit postharvest losses.

5. Conclusions

This study was conducted in a commercial cactus pear orchard to validate the effects of supplemental irrigation on the fruit yield, crop water use, fruit quality, and storability of 'Roja Lisa' cactus pear grown in the semiarid region of Mexico. This irrigation strategy is easily implemented on a farm scale. Although crop water use and water productivity were low in supplementally irrigated plants, total fruit yield, mean fruit mass, and commercial fruit yield were greater than in non-irrigated plants. These differences were more pronounced in growing seasons with low rainfall and vice versa. Fruit quality, measured as flesh firmness, was the same at harvest and maintained under both storage conditions (room temperature or cold room storage), but soluble solids concentration and dry mass of pulp were consistently low in supplementally irrigated fruit at harvest and under both storage conditions. An important finding was that the fruit mass loss rate was the lowest in those fruit receiving supplemental irrigation. This is very important for fruit storage, transportation, marketing, and final consumption. Therefore, this irrigation strategy is suggested for cactus pear growers with limited water availability for irrigation, and it corroborates our hypothesis. Cactus pear growers need more knowledge and training to efficiently manage supplemental irrigation applications.

Author Contributions: Conceptualization, J.A.Z. and V.M.-M.; Methodology, V.M.-M., J.A.Z., B.I.S.-T. and M.S.-P.; Formal analysis, J.A.Z., B.I.S.-T. and G.M.-G.; Investigation, V.M.-M., J.A.Z., R.K.C.-B., M.D.H., S.H.G.-M., B.I.S.-T., G.M.-G. and M.S.-P.; Resources, J.A.Z.; Data curation, V.M.-M., J.A.Z., R.K.C.-B., M.D.H., S.H.G.-M., B.I.S.-T., G.M.-G. and M.S.-P.; Writing—original draft preparation, V.M.-M. and J.A.Z.; Writing—review and editing, J.A.Z.; Supervision, J.A.Z.; Project administration, J.A.Z.; Funding acquisition, J.A.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research work was funding by the Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) through funding research project No. 8403134459.

Data Availability Statement: The datasets generated and/or analyzed during the current study are not publicly available because this information belongs to our sponsor (INIFAP), but they are available from the corresponding author upon reasonable request.

Acknowledgments: We highly appreciate the enthusiastic cooperation of Jesús Álvarez Gómez, the owner of the cactus pear orchard. We also thank Mary Lou Mendum (University California, Davis) for improving the final presentation of this document. We appreciate the valuable comments and suggestions from three reviewers.

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

References

1. Nhemachena, C.; Nhamo, L.; Matchaya, G.; Nhemachena, C.R.; Muchara, B.; Karuaihe, S.T.; Mpandeli, S. Climate change impacts on water and agriculture sectors in Southern Africa: Threats and opportunities for sustainable development. *Water* **2020**, *12*, 2673. [CrossRef]
2. Pereira, L.S. Water and agriculture: Facing water scarcity and environmental challenges. Invited overview paper. *CIGR J. Agric. Eng. Int.* **2005**, *VII*, 1–26.
3. Louhaich, M.; Nefzaoui, A.; Guevara, J.C. Cactus ecosystem goods and services. In *Crop Ecology, Cultivation and Uses of Cactus Pear*; Inglese, P., Mondragon, C., Nefzaoui, A., Sáenz, C., Eds.; The Food and Agriculture Organization of the United Nations and the International Centre for Agricultural Research in the Dry Areas: Rome, Italy, 2017; pp. 159–169.
4. Varnero, M.T.; Homer, I. Biogas production. In *Crop Ecology, Cultivation and Uses of Cactus Pear*; Inglese, P., Mondragon, C., Nefzaoui, A., Sáenz, C., Eds.; The Food and Agriculture Organization of the United Nations and the International Centre for Agricultural Research in the Dry Areas: Rome, Italy, 2017; pp. 187–193.
5. Potgieter, J.; D'Aquino, S. Fruit production and post-harvest management. In *Crop Ecology, Cultivation and Uses of Cactus Pear*; Inglese, P., Mondragon, C., Nefzaoui, A., Sáenz, C., Eds.; The Food and Agriculture Organization of the United Nations and the International Centre for Agricultural Research in the Dry Areas: Rome, Italy, 2017; pp. 51–71.
6. Prisa, D. *Opuntia ficus-indica* the key plant in climate change: Characteristics, cultivation and uses. *GSC Biol. Pharm. Sci.* **2021**, *17*, 94–105. [CrossRef]
7. Garcia de Cortázar, V.; Nobel, P.S. Biomass and fruit production for the prickly pear cactus, *Opuntia ficus-indica*. *J. Am. Soc. Hortic. Sci.* **1992**, *117*, 558–562. [CrossRef]
8. Nerd, A.; Karady, A.; Mizrahi, Y. Out-of-season prickly pear: Fruit characteristics and effect of fertilization and short droughts on productivity. *HortScience* **1991**, *26*, 527–529. [CrossRef]
9. Zegbe, J.A.; Serna-Pérez, A. Irrigation options to save water while enhancing export-size fruit and storability of 'Smooth Red' cactus pear. *J. Sci. Food Agric.* **2018**, *98*, 5503–5508. [CrossRef]
10. Konikow, L.F.; Kendy, E. Groundwater depletion: A global problem. *Hydrogeol. J.* **2005**, *13*, 317–320. [CrossRef]
11. Moreno-Vázquez, J.L.; Marañón-Pimentel, B.; López-Córdova, D. Los acuíferos sobrexplotados: Origen, crisis y gestión social. In *El Agua en México: Cauces y Encauces*; Jiménez-Cisneros, B., Torregorosa y Armenta, M.T., Arboites-Aguiliar, L., Eds.; Academia Mexicana de Ciencia y Consejo Nacional del Agua: Ciudad de México, México, 2010; pp. 79–115.
12. Postel, S.L. Entering an era of water scarcity: The challenges ahead. *Ecol. Appl.* **2000**, *10*, 941–948. [CrossRef]
13. Oweis, T.; Hachum, A. *Supplemental Irrigation: A Highly Efficient Water-Use Practice*; International Centre for Agricultural Research in the Dry Areas (ICARDA): Alepo, Syria, 2012; 16p.
14. Oweis, T.; Hachum, A. Improving water productivity in the dry areas of West Asia and North Africa. In *Water Productivity in Agriculture: Limits and Opportunities for Improvement*; Kijne, W.J., Barker, R., Molden, D., Eds.; CAB International: Wallingford, UK, 2003; Volume 1, pp. 179–197.
15. Acosta-Díaz, E.; Acosta-Gallegos, J.A.; Amador-Ramírez, M.D.; Padilla-Ramírez, J.S. Effect of supplemental irrigation on biomass and seed yield of rainfed dry bean in highlands of Mexico. *Agric. Téc. Méx.* **2009**, *35*, 157–167.
16. Abderrazzak, B.; Daoui, K.; Kajji, A.; Ibriz, M.; Dahan, R. Effects of supplemental irrigation and nitrogen applied on yield and yield components of bread wheat at the saïs region of Morocco. *J. Exp. Agric. Int.* **2013**, *3*, 904–913. [CrossRef]
17. Campos, P.F.; Júnior, J.A.; Casaroli, D.; Fontoura, P.R.; Evangelista, A.W.P. Varieties of sugarcane to supplemental irrigation in Brazilian savanna. *Eng. Agríc. Jaboticabal* **2014**, *34*, 1139–1149. [CrossRef]
18. Wale, A.; Sebnie, W.; Girmay, G.; Beza, G. Evaluation of the potentials of supplementary irrigation for improvement of sorghum yield in Wag-Himra, North Eastern, Amhara, Ethiopia. *Cogent Food Agric.* **2019**, *5*, 1664203. [CrossRef]
19. Cavalcante, E.S.; Feitosa de Lacerda, C.; Távora-Costa, R.N.; Gheyi, H.R.; Luzia-Pinho, L.; Sérvulo-Bezerra, F.M.; Cruz de Oliveira, A.; Florentino-Canjá, J. Supplemental irrigation using brackish water on maize in tropical semi-arid regions of Brazil: Yield and economic analysis. *Sci. Agric.* **2021**, *78* (Suppl. 1), e20200151. [CrossRef]
20. Razouk, R.; Ibijbijen, J.; Kajji, A. Optimal time of supplemental irrigation during fruit development of rainfed olive tree (*Olea europaea*, cv. Picholine Marocaine) in Morocco. *Am. J. Exp. Agric.* **2013**, *3*, 685–697. [CrossRef]
21. Van Der Merwe, L.L.; Wessels, A.B.; Ferreira, D.I. Supplemental irrigation for spineless cactus pear. *Acta Hortic.* **1997**, *438*, 77–82. [CrossRef]

22. Zegbe, J.A.; Servín-Palestina, M. Supplemental irrigation to save water while growing cactus pear in semi-arid regions. *Irrig. Drain.* **2021**, *70*, 269–280. [CrossRef]
23. Zegbe, J.A. Quality and storability of cactus pear fruit as improved by supplemental irrigation. *J. Prof. Assoc. Cactus Dev.* **2020**, *22*, 1–17.
24. Zegbe, J.A.; Mena-Covarrubias, J. Two reproductive bud thinning alternatives for cactus pear. *HortTechnology* **2010**, *20*, 202–205. [CrossRef]
25. Diaz-Pérez, J.C.; Shackel, K.A.; Sutter, E.G. Relative water content and water potential of tissue cultured apple shoots under water deficits. *J. Exp. Bot.* **1995**, *46*, 111–118. [CrossRef]
26. Pérez-Pérez, J.G.; Syvertsen, J.P.; Botía, P.; García-Sánchez, F. Leaf water relations and net gas exchange responses of salinized carrizo citrange seedlings during drought stress and recovery. *Ann. Bot.* **2007**, *100*, 335–345. [CrossRef]
27. Popescu, M.; Popescu, G.C. Diurnal changes in leaf photosynthesis and relative water content of grapevine. *Curr. Trends Nat. Sci.* **2014**, *3*, 74–81.
28. Tolk, J.A. Soils, permanent wilting points. In *Encyclopedia of Water Science*; Stewart, B.A., Howell, T.A., Eds.; Marcel Dekket Pub: New York, NY, USA, 2003; pp. 927–929.
29. Ghrab, M.; Masmoudi, M.M.; Ben Mechlia, N. Water productivity in fruit trees orchards under water scarcity. *Acta Hortic.* **2017**, *1150*, 317–322. [CrossRef]
30. Zegbe, J.A.; Serna-Pérez, A.; Mena-Covarrubias, J. Mineral nutrition enhances yield and affects fruit quality of 'Cristalina' cactus pear. *Sci. Hortic.* **2014**, *167*, 63–70. [CrossRef]
31. Smith, M.R.; Rao, I.M.; Merchant, A. Source-sink relationships in crop plants and their influence on yield development and nutritional quality. *Front. Plant Sci.* **2018**, *9*, 1889. [CrossRef] [PubMed]
32. Heldt, H.-W.; Piechulla, B. Phloem transport distributes photoassimilates to various sites of consumption and storage. In *Plant Biochemistry*, 5th ed.; Heldt, H.-W., Piechulla, B., Eds.; Academic Press: Cambridge, MA, USA, 2021; pp. 323–333.
33. Crisosto, C.H.; Johnson, R.S.; Luza, J.G.; Crisosto, G.M. Irrigation regimes affect fruit soluble solids concentration and rate of water loss of 'O'Henry' peaches. *HortScience* **1994**, *29*, 1169–1171. [CrossRef]
34. Mpelasoka, B.S.; Behboudian, M.H.; Dixon, J.; Neal, S.M.; Caspari, H.W. Improvement of fruit quality and storage potential of 'Braeburn' apple through deficit irrigation. *J. Hortic. Sci. Biotechnol.* **2000**, *75*, 615–621. [CrossRef]
35. Lufu, R.; Ambaw, A.; Opara, U.L. Water loss of fresh fruit: Influencing pre-harvest, harvest and postharvest factors. *Sci. Hortic.* **2020**, *272*, 109519. [CrossRef]
36. Cantwell, M. Post-harvest management of fruits and vegetable stems. In *Agro-Ecology, Cultivation, and Uses of Cactus Pear*; Barbera, G., Inglese, P., Pimienta-Barrios, E., Eds.; Plant Production and Protection 132; Food and Agriculture Organization of the United Nations: Rome, Italy, 1995; pp. 120–136.
37. Corrales García, J.; Hernández Silva, J.L. Cambios en la calidad postcosecha de variedades de tuna con y sin semilla. *Rev. Fitotec. Mex.* **2005**, *28*, 9–16.
38. Corrales Garcia, J.; Franco Moreno, F.; Rodriguez Campos, J. Fruit characterization of twenty accessions of cactus pear (*Opuntia* spp.) II. Changes in post-harvest. *Acta Hortic.* **2006**, *728*, 205–209. [CrossRef]
39. Maguire, K.M.; Lang, A.; Banks, N.H.; Hall, A.; Hopcroft, D.; Bennett, R. Relationship between water vapour permeance of apples and micro-cracking of the cuticle. *Postharvest Biol. Technol.* **1999**, *17*, 89–96. [CrossRef]
40. Faedda, R.; Daquino, S.; Granata, G.; Pane, A.; Palma, A.; Sanzani, S.M.; Schena, L.; Cacciola, S.O. Postharvest fungal diseases of cactus pear fruit in southern Italy. *Acta Hortic.* **2016**, *1144*, 215–218. [CrossRef]
41. Granata, G.; Faedda, R.; Ochoa, M.J. Diseases of cactus pear. In *Crop Ecology, Cultivation and Uses of Cactus Pear*; Inglese, P., Mondragon, C., Nefzaoui, A., Sáenz, C., Eds.; The Food and Agriculture Organization of the United Nations and the International Centre for Agricultural Research in the Dry Areas: Rome, Italy, 2017; pp. 115–123.