Quality and storability of cactus pear fruit as improved by supplemental irrigation

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ABSTRACT

This research evaluated some fruit quality attributes at harvest and after two storage conditions [i.e., room temperature and cold storage] of four cactus pear cultivars previously exposed to non-irrigated (NI) treatment as the control, supplemental irrigation (SI) and commercial irrigation (CI). The cultivars responded differently to irrigation treatments and among evaluations. SI and CI plants had the highest fruit and pulp mass at harvest and maintained at both storage conditions, although these results were not always significant. Flesh firmness tended to be the highest in SI and CI fruit at harvest in all cultivars. The latter response was maintained occasionally at both storage conditions in all cultivars. Both dry mass concentration and total soluble solids concentration tended to be the highest in NI fruit of all cultivars. Fruit mass loss was minimized by SI and CI treatments in both storage conditions, and in relation to room temperature storage, cold storage increased the fruit storage life of all cultivars. At the start of the experiment, NI fruit at room temperature storage had the highest decay incidence; after that, this fruit deterioration problem was observed occasionally in both storage conditions. It was concluded that the amount and occurrence of rain was an important factor in the statistical inconsistence of the response variables. However, the SI and CI treatments minimized fruit mass loss in both storage conditions and extended the fruit storage life of all cultivars in cold storage, which is important for transportation, marketing, and consumers. Additionally, SI, on a three-year-average, saved irrigation water by 51% compared to CI, therefore, SI may be recommended to similar agro-ecological regions.

***Keywords*: *Opuntia* spp.; fruit size; flesh firmness; total soluble solids; fruit mass loss.

INTRODUCTION

The fruit of the cactus pear (*Opuntia* spp.) is well appreciated worldwide not only as a Mexican exotic fruit but also for its active nutrients and multifunctional properties (Feugang *et al*., 2006; Santos-Díaz *et al*., 2017). This xerophytic plant is grown in marginal agricultural lands with low water availability in semi-arid and arid agro-ecosystems of America, Africa, Asia, Europe, and Oceania (Basile, 2001). Even when water for irrigation is the main limiting factor in these areas, cactus pear orchards have been shifted to utilize drip irrigation to improve productivity and fruit size (Nerd *et al*., 1989; García de Cortázar and Nobel, 1992; Mulas and D'hallewin, 1997; Gugliuzza *et al*., 2002; Zegbe and Serna-Pérez, 2018). Regardless of the fruit yield improvement, fruit quality attributes assessed at harvest from plants that were irrigated or not irrigated have produced mixed results. For instance, Mulas and D'hallewin (1997) found that fruit quality from irrigated plants was dependent on the cultivar, the percentage of pulp, dry mass and flesh firmness were lower in irrigated fruit than in non-irrigated fruit; while the total soluble solids concentration was higher in some irrigated cultivars than in others.

In contrast, Gugliuzza *et al*. (2002) found that the largest fruit mass and export-sized fruit was produced in irrigated plants, but the total soluble solids concentration was similar between irrigated and non-irrigated fruit. Regarding fruit mass and export-sized fruit, Zegbe and Serna-Pérez (2018) observed similar results to those of Gugliuzza *et al*. (2002). However, flesh firmness and peel mass tended to be higher in both irrigated and non-irrigated fruit, while both irrigation treatments produced similar outputs regarding pulp mass, total soluble solids concentration, and fruit dry mass concentration. Additionally, Zegbe and Serna-Pérez (2018) collected fruit from the same experiment and exposed fruit to room temperature storage for four weeks. After storing, the fruit quality assessment revealed that all fruit quality attributes evaluated were maintained similarly to their corresponding irrigation treatments evaluated at harvest, but irrigated fruit minimized fruit mass loss during storage.

Supplemental irrigation (SI) is another water-saving irrigation technology used to increase and stabilize annual crop yields in dry zones (Oweis and Hachum, 2003; Abderrazzak *et al*., 2013). The SI has also been applied to fruit crops such as olives (Razouk et al., 2013), peaches (Oweis and Hachum, 2012) and cactus pear (Van Der Merwe *et al*., 1997; Zegbe *et al*., 2019). Van Der Merwe *et al*. (1977) reported some fruit quality attribute improvements at harvest (e.g., fruit and pulp mass), they concluded that SI could not be justified in regions where the drought events occur occasionally due to the irrigation cost involved. The opposite was concluded by Zegbe *et al*. (2019), but additionally they saved water by 52% compared to commercially irrigated (CI) plants. Hence, this experiment was set up with four cactus pear cultivars to test the hypothesis that cactus pear plants under SI and CI would produce comparable responses in fruit quality attributes at harvest and maintained during room temperature and cold room storages. Storage life, in terms of fruit mass loss, was included because of its importance for handling, transportation to local and distant markets, and consumer acceptance and preference.

MATERIALS AND METHODS

Experimental place, vegetal material, and orchard management

The experiment was set up at the Campo Experimental Zacatecas, Calera, Zacatecas, Mexico (lat. 22°54'N, long. 102°39'W, elevation 2,197 m) from 2011 to 2013. The experimental site annually receives 416 mm of rainfall and 75% of it occurs between July and October. The mean annual pan evaporation is 1,609 mm. The annual mean temperature of the site is 14.6 °C. The orchard was established on a loam texture soil with 1.73% and 7.75 of organic matter content and pH, respectively.

The study included five-year-old plants of the following cactus pear cultivars: 'Amarilla Olorosa' (*O*. spp.; orange-pulped fruit), 'Cristalina' (*O. albicarpa* Scheinvar; white-pulped fruit), 'Dalia Roja' (*O*. spp.; red-pulped fruit), and 'Roja Lisa' [*O*. *ficus-indica* (L.) Mill.; red-pulped fruit]. The last two cultivars bear early-maturing fruit compared to the two former ones.
Plants were trained to an open vase system and spaced at 4 m x 3 m. Plants were handled with local agricultural practices (e.g., cladode pruning, fruit thinning, drip irrigation, fertigation, and weed and pest control as required). The orchard soil was covered with a mixture of native grass that was mowed periodically.

Treatments and experimental design

The treatments, as main plot, were: commercial irrigation (CI), where water depth was applied weekly to reach filed capacity (FC = 0.28 $m^3 m^{-3}$), supplemental irrigation (SI), where water depth was applied to reach FC every time the soil water content was approximately 0.14 $m^3 m^{-3}$, and non-irrigated (NI) as the rain-fed control. The subplots were the four cultivars above described that were randomly allocated within each block. The experimental unit comprising nine cactus pear plants per cultivar. The experiment was conducted in a split-block design. Briefly, during the growing seasons, soil water content was registered in all treatments and cultivars before and 24 h after each irrigation episode at a soil depth of 30 cm using time domain reflectometry (TDR, Mini-Trase System, Soil Moisture Equipment Corp., Santa Barbara, CA, USA). The latter information was used to estimate irrigation water depth applied and crop evapotranspiration (Zegbe and Serna-Pérez, 2012). The rainwater and relevant climatological information were acquired from an automated weather station (Adcon Telemetry System) placed at 1.8 km away from the experiment.

Postharvest experiment

Every growing season, from the experiment described above, eight fruits per replicate (twenty-four fruits per treatment) were randomly harvested from around the plants when the fruit skin color was either green-to-yellow ('Amarilla Olorosa'), green-to-white ('Cristalina') or green-to-red ('Roja Lisa' and 'Dalia Roja'). Every growing season, three groups of 72 fruits from each cultivar were formed. The fruit quality at harvest was assessed with the first group of fruits. The other two groups of fruits were stored each at cold storage or room temperature. The cold room was not available in 2011, but cold storage conditions were 10 ºC and 85% of relative humidity (RH) for 2012 and 10 ºC and 90% RH for 2013. At room temperature, the storage conditions were different for each cactus pear fruit due to their harvest time and the length of storage required to reach an 8% threshold of fruit mass loss to observe shrivel symptoms. So, room temperature conditions for 'Amarilla Olorosa' fruit were, on average, 25 ºC and 35% RH for 2011, 25 ºC and 39% RH for 2012, and 21 ºC and 52% RH for 2013. For 'Cristalina' fruit, the corresponding values were 25 ºC and 33% RH, 23 ºC and 39% RH, and 21 ºC and 52% RH, respectively. For both 'Roja Lisa' and 'Dalia Roja' fruit, the corresponding values were 24 ºC and 40% RH, 25 ºC and 37% RH, and 23 ºC and 35% RH, respectively. Before storing, the spines were removed, and the fruit was cured with a solution of copper sulphate (2.5 ml/L) and chlorine (1%). The experiments per cultivar at room temperature and cold storage were conducted in a completely randomized design.

Response variables

Fruit quality attributes consisted in separately measuring each individual fruit mass and pulp mass with precision balance (VE-303, Velab, USA). Flesh firmness was assessed doing two determinations on opposite sides on the equatorial area of each fruit with a penetrometer equipped with an 11.1-mm tip (model FT 327, Wagner Instruments, Greenwich, CT, USA). From each side of the fruit, several juice drops were collected and mixed and, with a digital refractometer (model PR-32α, Atago, Co. Ltd., Tokyo, Japan), total soluble solids concentration (ºBrix) was recorded. Composite samples of fresh pulp tissue (from three fruits) each of 25 g were oven-dried for two weeks at 60 °C to constant mass to determine the dry mass concentration of the fruit (the samples included the seeds). During both storage conditions, fruit mass loss was recorded weekly in each irrigation treatment by weighing each fruit individually until the 8% of fruit mass loss was observed.

Data analysis

The response variables were not compared among cactus pear cultivars because of the differences in their genetic background. Therefore, the information was analyzed separately using a completely randomized model with the general lineal models procedure of statistical analysis system (SAS Institute ver. 9.3, 2002-2010, Cary, NC, USA). Means of treatment were grouped by the Fisher's test at $p \leq 0.05$.

RESULTS

Fruit quality assessment at harvest and storability per cactus pear cultivar

In the 2011 growing season, the fruit quality evaluation of 'Amarilla Olorosa' at harvest revealed that the fruit mass and pulp mass from SI and CI plants were comparable. Although non-significant, those trends remained for the next two growing seasons. Yet, NI fruit maintained the lowest fruit mass values at room temperature in the three evaluated cycles and in cold storage in 2012 and 2013. The cold room was not available in 2011. This pattern was consistent for pulp mass at room temperature or cold storage, but it was higher in SI and CI fruit than NI fruit in 2013. At harvest, the flesh firmness was the highest in CI fruit in the 2011 growing season. The latter difference remained for room temperature fruit in 2012 only. The total soluble solids concentration was the greatest in NI fruit at harvest or room temperature in 2011. Dry mass concentration was maintained lower in CI fruit than in NI and SI fruit at room temperature in 2011 only (Table 1).

At harvest of 2011 and 2012, fruit mass and pulp mass of 'Cristalina' receiving NI treatment were lower than SI or CI treatments, and a similar trend was observed in the harvest of 2013. This result tended to be maintained for fruit mass at room temperature in 2012 and in cold storage in 2012 and 2013 as well as for pulp mass in cold storage in the 2012 evaluation. The flesh firmness at harvest was not modified by the irrigation treatments for the three growing seasons. At room temperature, the flesh firmness of the CI fruit was kept the highest in 2012 and in 2013 and at cold storage in 2013. The total soluble solids concentration was not modified by the irrigation treatments, except for the 2011 evaluation at harvest and at room temperature and cold storage in 2012, where CI fruit had the lowest values of the concentration of total soluble solids.

Table 1. Means values of some fruit quality attributes of 'Amarilla Olorosa' at harvest and after storage at room temperature or cold room from cactus pear plants undergoing irrigation treatments (ITs) for three consecutive growing seasons. The ITs were, non-irrigated (NI), supplemental irrigation (SI) and commercial irrigation (CI).

Fruit conditions/ITs	Fruit mass (g)			Pulp mass (g)			Flesh firmness (N)			Total soluble solid concentration (ºBrix)			Dry mass concentration (mg g^{-1} fresh mass)		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
At harvest															
NI	66.3b	87.7a	114.2a	34.9b	49.9a	58.3a	19.5b	21.4a	21.9a	14.9a	13.4a	13.1a	220.1a	184.7a	192.3a
SI	107.3a	95.1a	133.7a	51.1a	54.1a	68.3a	22.1b	20.4a	22.7a	14.3ab	13.3a	12.9a	215.8a	176.5a	200.3a
CI	113.9a	104.3a	132.3a	51.1a	53.4a	65.7a	29.5a	23.1a	24.2a	13.5b	13.5a	12.3a	212.0a	187.3a	199.0a
LSD	15.3	15.8	21.7	10.1	10.2	10.9	6.0	3.3	6.0	0.6	0.5	0.81	13.9	9.8	20.8
p > F	0.001	0.11	0.13	0.01	0.60	0.14	0.02	0.20	0.66	0.005	0.44	0.12	0.41	0.08	0.63
CV (%)	11.8	9.0	11.2	14.9	11.2	15.8	21.8	13.9	12.6	4.0	4.8	5.0	3.2	4.1	4.8
Room temperature															
NI	61.1b	69.1b	98.9b	41.2a	45.3a	59.3b	16.1a	12.0b	14.8a	13.1a	12.3a	12.4a	191.9a	154.9a	153.7a
SI	89.1a	86.7ab	114.7a	54.4a	55.9a	71.1a	15.7a	13.3ab	15.3a	12.1b	12.1a	12.1a	182.0a	144.2a	149.1a
CI	91.1a	95.1a	114.7a	53.3a	57.7a	70.9a	14.9a	16.5a	18.9a	11.6b	11.9a	11.8a	170.1b	151.2a	141.4a
LSD	15.5	18.6	9.3	13.2	13.8	6.0	3.2	3.6	2.5	0.6	1.1	0.47	10.8	13.9	11.2
p > F	0.01	0.04	0.002	0.09	0.14	0.005	0.76	0.05	0.66	0.003	0.70	0.14	0.01	0.24	0.5
CV (%)	15.0	12.5	8.0	18.4	14.7	10.4	19.5	22.2	12.3	5.2	5.8	6.6	2.6	7.4	4.9
Cold room															
NI	___	71.9b	104.5b	___	52.3a	63.3b	___	21.0a	18.9a	___	12.7a	11.8a	___	153.2a	141.4a
SI	___	84.1ab	130.6a	___	49.6a	77.8a	___	21.9a	19.5a	___	12.8a	11.2a	___	166.2a	133.6a
CI	___	94.4a	125.8a	___	43.4a	75.8a	___	23.4a	21.0a	___	12.8a	11.5a	___	161.3a	138.9a
LSD	___	17.1	22.7	___	12.5	9.4	___	2.9	4.2	___	0.8	0.6	___	20.0	14.4
p > F	___	0.05	0.016	___	0.27	0.02	___	0.20	0.48	___	0.95	0.14	___	0.31	0.44
CV (%)	___	14.2	8.4	___	15.3	11.5	___	17.8	15.1	___	5.5	5.3	___	7.5	5.7

Within fruit conditions and columns, mean values followed by the same lower-case letter were not significantly different by Fisher's least significant difference (LSD) ($p \leq 0.05$). The *p* > F and CV are the significance and the coefficient of variation, respectively.

The concentration of fruit dry mass concentration was similar among irrigation treatments either at harvest or at both storage conditions for the three growing seasons evaluated (Table 2). At harvest, the fruit mass and pulp mass of ‘Dalia Roja’ were the lowest in NI fruit in the three growing seasons. The latter was consistently maintained at room temperature and cold storage, except for pulp mass in cold storage in 2013, but the trend was similar. At harvest, the flesh firmness was lower in NI fruit than in SI and CI fruit in 2011, and it was maintained the lowest in NI fruit at room temperature and cold storage in 2013. The SI and CI fruit had the lowest total soluble solid concentration at harvest in the three growing seasons. This pattern was maintained at the room temperature evaluation for 2011 and 2012 and in the cold storage evaluation for 2012 and 2013. The concentration of dry mass concentration was lower in SI and CI fruit than in NI fruit in 2012 at harvest. This pattern was kept at the room temperature evaluation for the three growing seasons and in the cold storage evaluation for 2012 (Table 3).

The ‘Roja Lisa’ fruit mass was higher in SI and CI than in NI plants at harvest in 2011 and 2012, and this trend was maintained in 2013. The irrigation treatments did not affect the pulp mass at harvest in the three evaluated cycles, while this response variable was maintained as being higher in SI fruit and CI fruit than in NI fruit either at room temperature or cold storage in 2012 and 2013. The highest flesh firmness at harvest in 2011 and 2012 was observed in SI and CI fruit. The latter was maintained consistent at room temperature storage for 2012 and 2013, but no measurable changes in flesh firmness were observed in the cold storage assessments in 2012 and 2013. The CI fruit had the lowest total soluble solids concentration at harvest and at both storage conditions, except for 2013 in cold storage. The dry mass concentration was reduced in SI and CI fruit at room temperature in 2012 only (Table 4).

Fruit mass loss

In the 2011 evaluation, the cold room was not available, but the RT storage reveled that, compared to NI fruit, SI and CI fruit from all cultivars minimized fruit mass loss (data not shown). This pattern was consistent for the 2012 evaluation in both storage conditions, except for ‘Amarilla Olorosa’ in cold storage (Figure 1B). In 2013 the same patter was consistent for ‘Amarilla Olorosa’ (Figure 2A), ‘Dalia Roja’ (Figure 2E), and ‘Roja Lisa’ (Figure 2G and 2H).

Fruit decay incidence

Room temperature storage

In 2011 evaluation at room temperature storage, NI treatment produced the highest fruit decay incidence in all cactus pear cultivars followed by SI treatment in ‘Cristalina’ and ‘Dalia Roja’ cultivars and by CI treatment in ‘Dalia Roja’. No fruit decay incidence was observed in any other irrigation treatment or cactus pear cultivar (Table 5). In 2012, a 4.2% of fruit decay incidence was observed only in ‘Cristalina’ and ‘Roja Lisa’ fruit from plants exposed to SI and NI, respectively. In the 2013 evaluation, fruit decay incidence was observed only in ‘Amarilla Olorosa’ plants where the highest fungi infection was observed in SI fruit (Table 5).

Table 2. Means values of some fruit quality attributes of 'Cristalina' at harvest and after storage at room temperature or cold room from cactus pear plants undergoing irrigation treatments (ITs) for three consecutive growing seasons. The ITs were, non-irrigated (NI), supplemental irrigation (SI) and commercial irrigation (CI).

Fruit conditions/ITs	Fruit mass (g)			Pulp mass (g)			Flesh firmness (N)			Total soluble solid concentration (ºBrix)			Dry mass concentration (mg g^{-1} fresh mass)		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
At harvest															
NI	90.4b	124.3c	170.7a	56.3b	78.0c	107.3a	30.6a	26.3a	29.8a	13.4a	13.1a	13.6a	193.7a	167.5a	199.7a
SI	175.2a	148.3b	185.0a	111.0a	93.5b	118.5a	27.3a	24.3a	30.5a	13.6a	12.6a	13.4a	185.3a	161.2a	191.2a
CI	184.3a	179.0a	197.9a	110.6a	108.6a	119.3a	31.7a	27.2a	31.5a	13.0b	11.9a	13.6a	176.1a	158.8a	193.9a
LSD	62.6	20.8	27.2	2.4	14.6	15.7	8.4	2.4	3.1	0.3	0.6	0.8	17.6	13.4	18.5
p > F	0.02	0.002	0.09	0.03	0.01	0.19	0.45	0.33	0.44	0.01	0.01	0.60	0.08	0.33	0.55
CV (%)	18.7	13.0	9.9	20.1	15.1	11.1	24.9	16.8	18.1	5.5	5.3	5.3	4.2	10.2	5.8
Room temperature															
NI	111.8a	128.2b	175.5a	78.0a	91.3b	123.4a	27.5a	18.6b	21.0b	12.3a	12.8a	12.8a	162.5a	144.1a	155.4a
SI	171.9a	153.3b	193.0a	118.6a	110.4ab	137.4a	28.0a	19.3b	23.5a	12.9a	12.4a	12.3a	142.9a	137.6a	150.1a
CI	205.7a	193.2a	195.4a	134.9a	129.1a	137.0a	25.0a	25.3a	24.8a	12.5a	11.2b	12.0a	146.2a	128.3a	142.7a
LSD	101.4	28.3	23.7	66.7	23.7	20.4	9.1	2.5	2.4	2.0	1.2	0.9	31.5	2.4	13.7
p > F	0.15	0.004	0.19	0.21	0.02	0.25	0.44	0.001	0.02	0.68	0.03	0.16	0.32	0.08	0.15
CV (%)	14.3	12.3	7.1	15.9	13.5	7.6	13.4	12.5	13.7	4.6	3.9	5.2	6.0	13.7	7.4
Cold room															
NI	___	121.4c	163.9b	___	87.2b	115.2a	___	18.8b	29.9a	___	13.0a	12.3a	___	167.6a	165.8a
SI	___	149.8b	188.8a	___	106.0a	129.7a	___	17.9b	31.5a	___	12.6ab	12.0a	___	160.1a	165.2a
CI	___	186.0a	198.3a	___	120.5a	136.0a	___	24.6a	32.2a	___	11.5b	12.1a	___	154.0a	164.2a
LSD	___	20.9	21.0	___	15.1	20.8	___	5.1	4.3	___	1.1	0.8	___	2.4	18.1
p > F	___	0.001	0.03	___	0.005	0.08	___	0.03	0.47	___	0.05	0.52	___	0.5	0.98
CV (%)	___	11.9	8.8	___	14.2	10.0	___	19.0	11.8	___	4.6	5.5	___	11.8	6.4

Within fruit conditions and columns, mean values followed by the same lower-case letter were not significantly different by Fisher's least significant difference (LSD) ($p \leq 0.05$). The *p* > F and CV are the significance and the coefficient of variation, respectively.

Table 3. Means values of some fruit quality attributes of 'Dalia Roja' at harvest and after storage at room temperature or cold room from cactus pear plants undergoing irrigation treatments (ITs) for three consecutive growing seasons. The ITs were, non-irrigated (NI), supplemental irrigation (SI) and commercial irrigation (CI).

Fruit conditions/ITs	Fruit mass (g)			Pulp mass (g)			Flesh firmness (N)			Total soluble solid concentration (ºBrix)			Dry mass concentration (mg g^{-1} fresh mass)		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
At harvest															
NI	92.9b	126.3b	142.3b	61.8b	78.7b	95.0b	22.4b	19.4a	18.8a	14.3a	13.1a	12.0a	198.5a	182.0a	169.9a
SI	169.4a	166.4a	173.0a	96.8a	104.3a	111.7a	27.9a	20.3a	22.0a	12.8b	12.7b	11.3ab	192.7a	171.7b	163.8a
CI	169.0a	178.3a	179.1a	96.3a	105.3a	112.3a	27.2a	19.1a	20.8a	12.5b	12.2b	10.9b	190.6a	168.7b	152.4a
LSD	20.0	37.1	24.3	16.8	22.7	12.8	4.0	4.4	3.8	0.9	0.5	0.8	8.0	8.5	22.9
$p > F$	0.0001	0.03	0.02	0.003	0.05	0.03	0.03	0.80	0.19	0.007	0.01	0.05	0.12	0.01	0.24
CV (%)	15.4	11.3	8.5	19.2	13.8	10.8	12.3	14.8	12.8	5.1	5.1	5.7	3.3	4.0	2.8
Room temperature															
NI	72.6b	116.0b	136.1b	43.6b	79.0b	79.5b	12.1a	10.8a	6.1b	14.4a	12.8a	11.7a	177.7a	147.0a	142.1a
SI	136.7a	146.0a	170.1a	84.7a	100.2a	122.9a	12.3a	14.5a	12.1a	12.4b	12.3b	11.8a	137.8b	136.9b	137.0a
CI	141.9a	152.6a	169.6a	87.0a	101.3a	127.5a	11.6a	12.7a	10.6a	12.3b	12.0b	11.5a	141.8b	135.7b	118.1b
LSD	28.4	21.8	20.6	20.4	16.8	18.0	2.6	3.9	4.4	0.9	0.4	1.1	28.0	10.0	10.1
$p > F$	0.002	0.01	0.01	0.004	0.03	0.001	0.68	0.14	0.04	0.004	0.02	0.79	0.03	0.05	0.003
CV (%)	14.6	12.4	10.2	18.6	14.0	14.9	19.6	27.0	26.9	4.8	7.6	7.3	7.1	5.8	8.8
Cold room															
NI	___	118.7b	152.1b	___	85.1b	110.7a	___	18.9a	16.0b	___	13.1a	11.9a	___	148.5a	143.6a
SI	___	151.8a	193.7a	___	106.2a	139.8a	___	23.8a	19.3a	___	12.0b	11.4ab	___	124.1b	141.0a
CI	___	166.3a	179.3ab	___	112.0a	121.9a	___	21.8a	20.1a	___	12.4b	10.7b	___	118.7b	138.5a
LSD	___	25.5	23.3	___	19.0	29.1	___	5.9	3.0	___	0.3	0.7	___	13.6	15.2
$p > F$	___	0.01	0.05	___	0.03	0.07	___	0.20	0.03	___	0.001	0.01	___	0.001	0.73
CV (%)	___	10.8	10.7	___	11.2	12.3	___	17.4	15.0	___	5.7	6.6	___	8.5	4.6

Within fruit conditions and columns, mean values followed by the same lower-case letter were not significantly different by Fisher's least significant difference (LSD) ($p \leq 0.05$). The $p > F$ and CV are the significance and the coefficient of variation, respectively.

Table 4. Means values of some fruit quality attributes of 'Roja Lisa' at harvest and after storage at room temperature or cold room from cactus pear plants undergoing irrigation treatments (ITs). The ITs were, non-irrigated (NI), supplemental irrigation (SI) and commercial irrigation (CI) for three consecutive growing seasons.

Fruit conditions/ITs	Fruit mass (g)			Pulp mass (g)			Flesh firmness (N)			Total soluble solid concentration (ºBrix)			Dry mass concentration (mg g^{-1} fresh mass)		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
At harvest															
NI	88.5b	96.3b	116.0a	48.7a	60.7a	65.5a	28.2b	21.0b	36.7a	14.4a	14.1a	11.4a	229.0a	198.4a	201.8a
SI	105.2a	97.6b	127.9a	50.0a	53.3a	69.7a	40.5a	21.6b	38.5a	13.3b	13.0b	11.4a	228.6a	196.0a	201.8a
CI	106.6a	116.8a	129.8a	52.7a	60.7a	67.6a	36.5a	26.6a	42.1a	13.7b	13.2b	10.7b	231.1a	203.9a	198.8a
LSD	16.5	16.8	13.8	8.4	10.4	7.1	6.2	4.5	10.5	0.6	0.6	0.6	9.2	15.8	7.3
p > F	0.06	0.04	0.08	0.53	0.30	0.41	0.008	0.05	0.49	0.01	0.01	0.02	0.84	0.5	0.27
CV (%)	11.3	12.0	11.9	15.0	12.7	12.6	17.6	16.5	12.7	3.7	3.9	5.9	7.0	5.3	2.0
Room temperature															
NI	84.6a	81.1b	102.1b	49.5a	49.5b	60.4b	20.6a	15.3b	16.1b	13.1a	13.0a	10.7a	205.4a	184.9a	156.8a
SI	97.9a	99.7ab	138.3a	56.6a	63.4a	84.0a	20.2a	16.1b	21.1a	13.1a	12.2b	10.3ab	203.2a	160.9c	144.2a
CI	102.3a	112.0a	139.5a	56.9a	63.3a	78.9a	22.3a	22.9a	21.1a	12.6a	12.1b	10.1b	198.3a	176.3b	154.3a
LSD	25.4	19.0	19.3	13.5	9.3	12.0	5.6	3.0	3.3	1.3	0.4	0.50	5.1	8.5	14.1
p > F	0.30	0.02	0.005	0.40	0.02	0.007	0.60	0.001	0.01	0.51	0.004	0.05	0.30	0.001	0.15
CV (%)	13.2	9.7	10.0	16.7	11.0	13.3	21.0	22.8	18.6	5.3	4.4	4.2	3.6	3.3	3.7
Cold storage															
NI	___	91.8b	103.1b	___	60.8b	63.7b	___	28.5a	26.0a	___	13.2a	10.6a	___	155.5a	160.9a
SI	___	110.7a	128.3a	___	64.0ab	75.4a	___	27.6a	32.5a	___	12.9a	10.8a	___	145.2a	160.8a
CI	___	110.2a	139.4a	___	71.2a	84.7a	___	33.0a	32.3a	___	12.3b	10.5a	___	155.0a	156.4a
LSD	___	10.5	15.1	___	7.7	9.7	___	4.8	6.5	___	0.4	0.5	___	16.8	12.2
p > F	___	0.01	0.003	___	0.4	0.006	___	0.07	0.08	___	0.006	0.32	___	0.31	0.61
CV (%)	___	10.0	9.1	___	11.0	13.6	___	14.1	13.5	___	5.0	5.4	___	6.4	7.4

Within fruit conditions and columns, mean values followed by the same lower-case letter were not significantly different by Fisher's least significant difference (LSD) ($p \leq 0.05$). The *p* > F and CV are the significance and the coefficient of variation, respectively.

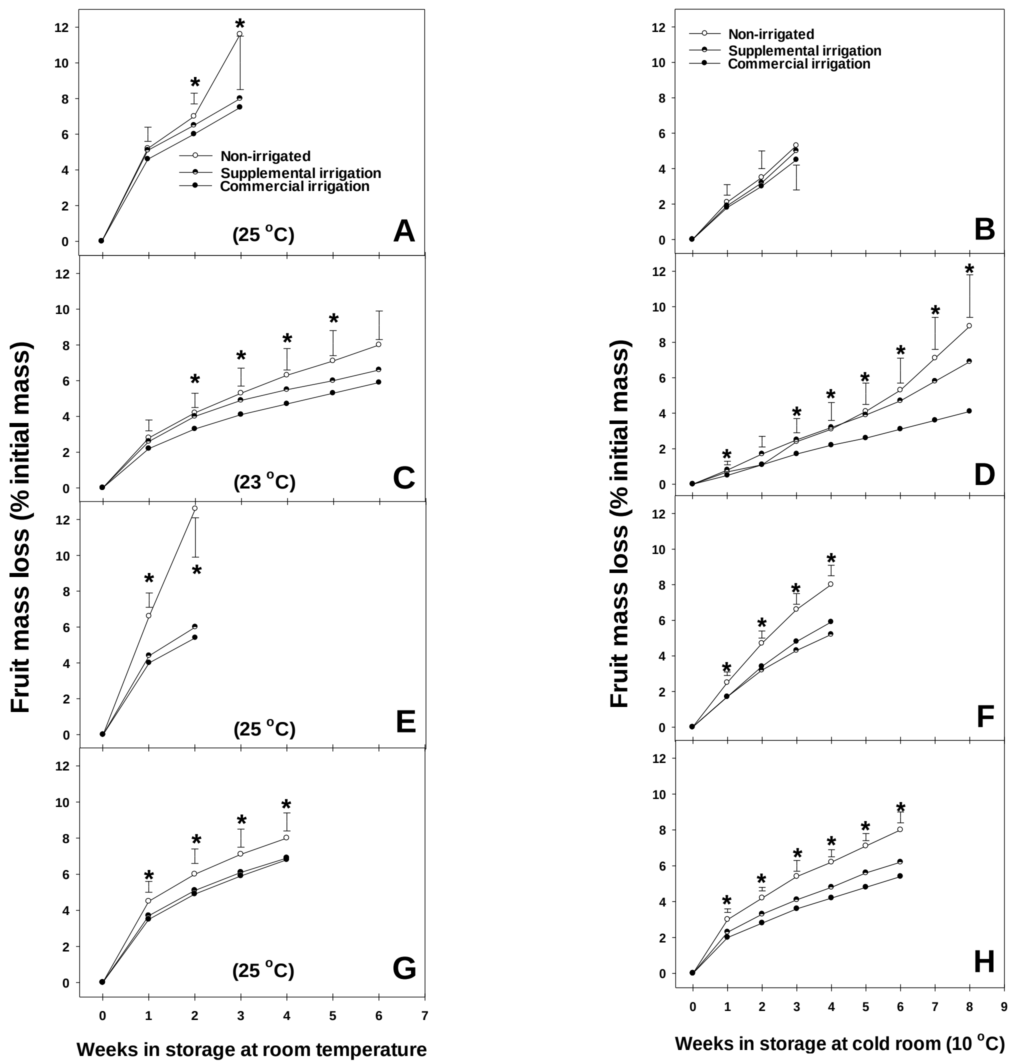

Figure 1. Cumulative fruit mass loss of ‘Amarilla Olorosa (A and B), ‘Cristalina’ (C and D), ‘Dalia Roja’ (E and F), and ‘Roja Lisa’ (G and H) fruit at two storage conditions from cactus pears plants undergoing irrigation treatments in 2012. At each sample date (n = 24), vertical bars indicate Fisher’s least significant difference values and the asterisks represent statistical differences ($p \leq 0.05$).

Cold storage

The cold room was not available in the 2011 evaluation. In 2012, SI treatment induced a 4.2% of fruit decay incidence in ‘Amarilla Olorosa’, ‘Cristalina’ and ‘Dalia Roja’. No fungi infection was observed in ‘Roja Lisa’ fruit at any irrigation treatment. In contrast, ‘Amarilla Olorosa’ fruit had no decay incidence at any irrigation treatment in 2013 evaluation. The same was true for NI fruit of ‘Cristalina’ and ‘Dalia Roja’ in the same evaluation. However, the highest fruit decay incidences were observed for ‘Cristalina’ and ‘Roja Lisa’ in CI and NI fruit, respectively (Table 5).

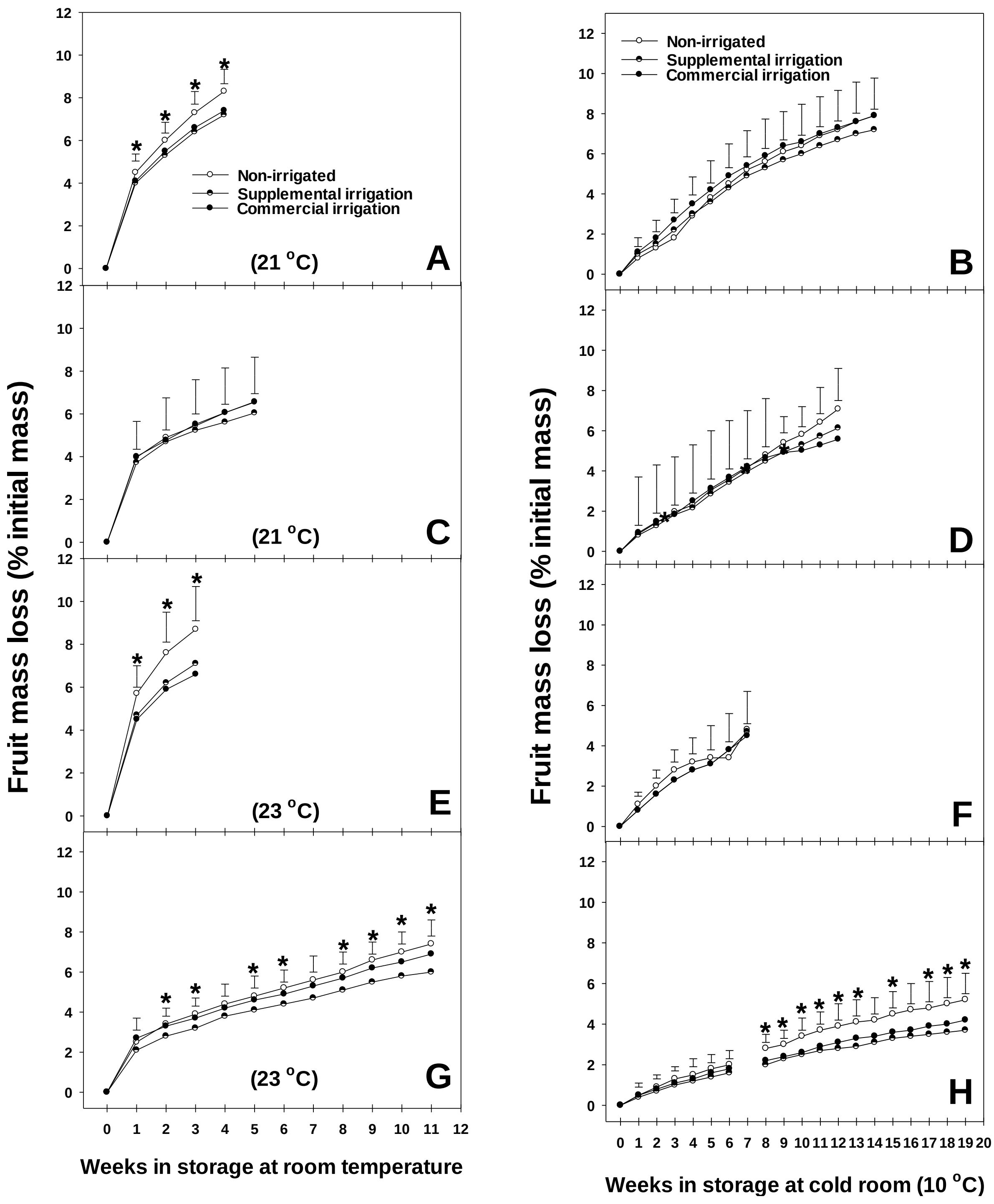

Figure 2. Cumulative fruit mass loss of 'Amarilla Olorosa (A and B), 'Cristalina' (C and D), 'Dalia Roja' (E and F), and 'Roja Lisa' (G and H) fruit at two storage conditions from cactus pears plants undergoing irrigation treatments in 2013. At each sample date (n = 24), vertical bars indicate Fisher's least significant difference values and the asterisks represent statistical differences ($p \leq 0.05$).

Table 5. Fruit decay incidence (%) assessed in *Opuntia* cultivars exposed to storage conditions from cactus pear plants undergoing irrigation treatments (ITs). The ITs where non-irrigated (NI), supplemental irrigation (SI) and commercial irrigation (CI) for three consecutive growing seasons.

	Storage conditions							
	Room temperature				Cold room			
Year/ITs	'Amarilla Olorosa'	'Cristalina'	'Dalia Roja'	'Roja Lisa'	'Amarilla Olorosa'	'Cristalina'	'Dalia Roja'	'Roja Lisa'
2011								
NI	50.0	87.5	41.7	33.3	——	——	——	——
SI	0	12.5	20.8	0	——	——	——	——
CI	0	0	8.3	0	——	——	——	——
2012								
NI	0	0	0	4.2	0	0	0	0
SI	0	4.2	0	0	4.2	4.2	4.2	0
CI	0	0	0	0	0	0	0	0
2013								
NI	4.2	0	0	0	0	0	0	8.3
SI	8.3	0	0	0	0	8.3	4.2	4.2
CI	4.2	0	0	0	0	25.0	4.2	4.2

DISCUSSION

In arid and semi-arid lands, there are commercially important xerophytic plants such as *Opuntia* spp.; however, water for irrigation is the main limiting factor for agricultural purposes. Therefore, irrigation strategies to save water and increase crop yields are a challenge (Oweis and Hachum, 2003). Cactus pear (*Opuntia* spp.) has been a good example in combining the latter two issues in different arid and semi-arid regions worldwide (Nerd *et al*., 1989; García de Cortázar and Nobel, 1992; Mulas and D'hallewin, 1997; Gugliuzza *et al*., 2002; Zegbe and Serna-Pérez, 2018). Consequently, this experiment was set up to assess, among other cactus pear plant responses [e.g., water efficiencies, yield and yield components, whose information is not given here], fruit quality at harvest and storage conditions from plants undergoing CI, SI, and NI.

The improvement of fruit size at harvest and its maintenance in both storage conditions, in terms of fruit mass and pulp mass (Table 1-4), in all cactus pear cultivars can be explained by the application of irrigation itself in favor of normal photosynthesis performance (Nobel and Hartsock, 1984; Nobel, 1994). Fruit was also thinned (Zegbe and Serna-Pérez, 2018); therefore, fruit thinning plus the irrigation made more carbohydrates available to be partitioned towards the fruit (DeJong and Grossman, 1994; Miranda-Jiménez and Royo-Díaz, 2002), and then, reflected in fruit size, in terms of fruit mass and pulp mass. Contrary to the study of Mulas and D'hallewin (1997), Zegbe and Serna-Pérez (2018) found that CI and partial rootzone drying irrigation enhanced flesh firmness, and it was confirmed here because SI and CI plants tended to produce fruit with higher flesh firmness than NI plants at harvest and sometimes maintained in both storage conditions in all cultivars (Table 1-4). Although, this research work was not created as a cell-level study, this result suggests that, compared with NI fruit, SI and CI plants produced fruit with cells that are more densely packed that enhanced flesh firmness (Ebel *et al*., 1993). In this experiment, for example, 'Amarilla Olorosa' flesh firmness correlated positively with fruit mass at harvest (r = 0.22; p = 0.06) or room temperature (r = 0.31; 0.01) and cold storage (r = 0.44; p = 0.0001). The same occurred with 'Roja Lisa' fruit at harvest (*r* = 0.52; *p* = 0.0001) and room temperature (r = 60; *p* = 0.0001). The latter examples are contrary to apples (Mpelasoka *et al*., 2000) and peaches (Crisosto *et al*., 1994), because a large fruit correlated negatively with flesh firmness at harvest and after storage (DeEll *et al*., 1999).

Most of the time, NI plants produced lower fruit mass and pulp mass than SI and CI plants; however, the former treatment yielded the highest total soluble solid concentrations and dry mass concentration of fruit (Table 1-4). Therefore, lower total soluble solid concentrations in CI and SI fruits could be due to a dilution effect because of fruit cells of SI and CI plants may have contained higher water content than NI fruit cells. This phenomenon has been seen in apples (Ebel *et al*., 1993; Mpelasoka *et al*., 2000) and in tomatoes (Zegbe-Domínguez *et al*., 2003) undergoing deficit irrigation treatments. So, the correlation between pulp mass with total soluble solid concentrations and dry mass concentration of 'Cristalina' fruit was moderate and negative (*r* = -0.45; *p* = 0.001 and *r* = -0.61; *p* = 0.001, respectively). The corresponding values for 'Dalia Roja', in the same order, were: *r* = -0.13 (*p* = 0.05) and *r* = -0.34 (*p* = 0.01) and for 'Roja Lisa' were: *r* = -0.40 (*p* = 0.0005) and *r* = -0.54 (*p* = 0.02). The exception was 'Amarilla Olorosa' cultivar, whose response variables did not correlate each other, therefore, there was no additional information to offer a comprehensible explanation to this respect.

After harvest, the storability of *Opuntia's* fruit depends on the cultivar, cultivation conditions, fruit maturation stage, and storage facilities (Schirra *et al*., 1999). During storage, fruit mass loss takes place mainly via transpiration (Corrales-García and Hernández-Silva, 2005; Corrales-García *et al*., 2006). For this fruit, the fruit mass loss threshold for visible changes in fruit appearance (e.g., shriveling and wilting) and fruit texture (e.g., flaccidity and softening) has been set at 8% (Cantwell, 1995). In this experiment, most of the times, fruit from SI and CI plants minimized fruit mass loss in all cultivars in both storage conditions and extended their storage life in cold storage (Figure 1 and 2).

The water vapour movement from the aerial parts of the plants (e.g., fruit) to the atmosphere is partially limited by the cuticle and the epicuticular waxes (Tafolla-Arellano, 2013). Consequently, the results suggest that SI and CI treatments may have made positive changes at the level of the epidermis (Maguire *et al*., 1999), maybe better cuticle or epicuticular waxes deposition and distribution on the fruit epidermal cells (Crisosto *et al*., 1993), might have resulted in less fruit mass loss, as found in other postharvest studies conducted with *Opuntia*'s fruit (Schirra *et al*., 1999; Lopez-Castañeda *et al*., 2010), peaches previously exposed to various irrigation regimens (Crisosto *et al*., 1994), and plums exposed to different O_3 concentrations (Crisosto *et al*., 1993). So, in relation to room temperature, cold storage increased storage life by 250% for 'Amarilla Olorosa', 40% for 'Cristalina', 100% for 'Dalia Roja', and 73% for 'Roja Lisa'. The latter finding is crucial for transportation, marketing, and final consumers. However, after this study, the threshold of fruit mass loss (8%) established by Cantwell (1995) must be reconsidered for each cactus pear cultivar. Nerveless, as seen in Figures 1 and 2, the storage life was influenced, in part, by the growing season (mainly by the presence of precipitation), cultivar, and storage conditions.

Decay incidence and chilling injury in cactus pear fruit depends on the cultivar, fruit maturation stage, and storage conditions (Schirra *et al*., 1999). The outputs of this experiment agree, in part, with the latter authors, because while chilling injury was not present, decay incidence was observed on NI fruit of 'Cristalina' at room temperature (87.5%) in 2011. After that, in 2012 and 2013, decay incidence ranged from no fungi infection to 25% of decay incidence, which may be attributable to orchard management (e.g., irrigation treatments, pest and disease control, etc.) and fruit handling before storing. The latter consisted in removing the spines from the fruit followed for a fruit chemical treatment (a solution of copper sulfate + chlorine) against pathogens. Changes in the cuticle or epicuticular waxes deposition and distribution (which deserves to be further researched) could have contributed also limiting pathogens entry in favor of longer storing life and fruit quality appearance (Cruz-Bravo *et al*., 2019; Zegbe *et al*., 2019). Nevertheless, it is imperative to identify and specify what pathogens are involved in fruit decay, because at least *Fusarium* spp., *Alternaria* spp., *Chlamydomyces* spp., and *Penicillium* spp. are implicated in this postharvest problem (Granata *et al*., 2017).

In 2013, most of the response variables observed no measurable changes at harvest (Fig. 1-4). During this growing season, the precipitation started earlier than the two previous ones (on June 21, 23, and 9 for 2011, 2012, and 2013, respectively). Additionally, the amounts of precipitation were also greater in 2013 than in the 2011 and 2012 growing seasons for all cultivars, but in particular, the late-maturing ones ('Amarilla Olorosa' and 'Cristalina'). The early-maturing cultivars '(Roja Lisa' and 'Dalia Roja') received 50, 71, and 182 mm of precipitation in 2011, 2012, and 2013, respectively; while the latter cultivar received 102, 86, and 213 mm for 2011, 2012, and 2013, respectively. This may override the effect of SI and CI treatments, as pointed out by Van Der Merwe *et al*. (1997), for cactus pear grown under Pretoria's conditions. Unfortunately, a rainy year occurs occasionally in this agro-ecological region so that SI would be a good irrigation strategy for the enhancement fruit quality and storability while large amounts of water are saved (on average 51%) on the cactus pear cultivation.

CONCLUSIONS

After three consecutive evaluations, the outputs from this experiment suggest that SI and CI plants had the highest fruit mass and pulp mass at harvest, and both parameters were maintained in both storage condition evaluations. Flesh firmness tended to be the highest in SI and CI fruit at harvest in all cultivars. The latter response was maintained occasionally in both storage condition in all cultivars. The NI fruit tended to observe the highest dry mass concentration and soluble solids concentration at harvest and in both storage condition evaluations.

Fruit mass loss was minimized in those fruit from SI and CI treatments in both storage conditions, and therefore, increased their storage life in those fruit stored at cold room. At the start of the experiment, NI fruit at room temperature had the highest decay incidence; after that, it was observed occasionally in both storage conditions, and the percentage ranged between 4.2% and 25%. Although the information was not reported here, relative to CI treatment, on average, SI treatment saved irrigation water by 51%. Therefore, SI may be recommended over CI for those regions with similar or drier agro-ecological conditions.

ETHICS STATEMENT

Not applicable" in this publication.

CONSENT FOR PUBLICATION

Not applicable" in this publication.

AVAILABILITY OF SUPPORTING DATA

The datasets generated and/or analyzed during the current study are not publicly available due to this information belongs to the sponsor (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias) but are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors have declared that no competing interests exist**.**

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AUTHOR CONTRIBUTIONS

Conceptualization; Methodology; Formal analysis; Investigation; Resources; Data curation; Writing-original draft preparation; Writing-review and editing; Supervision; Project administration; Funding acquisition by J.A. Zegbe.

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