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Research Article

Effects of different training systems and limited irrigation applications on cold storage of pitaya (*Hylocereus* spp.) fruits

Mustafa UNLU[1], Lokman ALTINKAYA[2], Hamide GUBBUK[3]*, Harun KAMAN[4]

[1]*Alata Horticultural Research Institute, 33740 Mersin, Türkiye; unlu.mustafa@tarimorman.gov.tr*
[2]*Akdeniz University, Kumluca Vocational School, Department of Plant and Animal Production, 07350 Antalya, Türkiye; altinkaya@akdeniz.edu.tr*
[3]*Akdeniz University, Faculty of Agriculture, Department of Horticulture, 07059 Antalya, Türkiye; gubbuk@akdeniz.edu.tr (*corresponding author)*
[4]*Akdeniz University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, 07059 Antalya, Türkiye; hkaman@akdeniz.edu.tr*

Abstract

Pitaya is a species valued for its aesthetically pleasing fruit, multifunctional uses, ability to bear fruit within a year of planting, and strong market potential. These characteristics have contributed to cultivation of subtropical regions. However, research on the postharvest storage of pitaya is limited, and existing studies show variability in storage conditions. Additionally, no studies have explored the effects of different training systems and deficit irrigation applications on pitaya storage. This study evaluated the effects of three training systems (Pole System, T-System, and Inverted U-System) and four irrigation regimes (FULL irrigation, 75%, 50%, and 25% deficit irrigation) on the cold storage quality of 'Vietnamese Jaina' pitaya cultivars' fruits. The fruits were stored at 10 °C and 80% relative humidity, and key quality parameters titratable acidity (TA), total soluble solids (TSS), weight loss, ascorbic acid content, sugar composition (glucose, fructose, sucrose), and antioxidant activity were measured at 10-day intervals. Results showed a gradual increase in weight loss (from 1.52% to 3.10%) and a decrease in ascorbic acid content (from 39.7 mg kg^{-1} to 32.9 mg kg^{-1}) over storage. Sugar concentrations (glucose, fructose, sucrose) and antioxidant activity increased up to day 20 before declining. While irrigation treatments had minimal effects on most parameters, training systems significantly influenced fruit quality. The Pole System (Control) exhibited the highest TSS and ascorbic acid content, while the T-System had the highest glucose and sucrose concentrations. The greatest antioxidant activity was found in the Inverted U-System. The results indicate that 'Vietnamese Jaina' pitaya fruit can be stored for up to 20 days at 10 °C and 80% relative humidity in all training systems and irrigation regime without significant loss of quality.

Keywords: deficit irrigation; dragon fruit; pole system; water use efficiency

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Introduction

Global climate change has recently intensified drought, making it one of the most pressing global challenges. This situation has led to increased interest in growing more drought-tolerant crops that require less

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water and provide higher economic returns. Pitaya is one of the most important drought species. It is grown in several regions of the world, including southern Florida and Hawaii in the United States, the Caribbean, Australia, Taiwan, Vietnam, Malaysia and Israel. In recent years, pitaya production has also expanded in Turkey, particularly in the Mediterranean and Aegean regions, where subtropical climates prevail, and is mainly grown in greenhouses. The first commercial marketing of pitaya began in Vietnam in 1995 (Mizrahi, 2015), and today there is growing interest in pitaya in European markets. This increase in demand is not only due to its consumption as a fresh fruit but also to the fact that it has a wide range of applications in the food industry. In addition, the fruit's eye-catching appearance, drought tolerance, and high levels of health-promoting functional compounds have increased its consumption and commercial production (Stintzing *et al.*, 2003; Zhuang *et al.*, 2012; Mello *et al.*, 2015; Ferreres *et al.*, 2017). Pitaya is particularly rich in vitamin C (ascorbic acid), phenolic compounds and antioxidants (Jaafar *et al.*, 2009; Tenore *et al.*, 2012), and its low fat, high water and high fibre content make it a good diet fruit. The external appearance, aroma, and taste of pitaya are key quality attributes that are influenced by environmental conditions, cultivation practices, and postharvest treatments (Jiang *et al.*, 2020). As a non-climacteric fruit, pitaya does not ripen after harvest, so it must reach optimal maturity before harvest (Mizrahi and Nerd, 1999; Chien *et al.*, 2007). In tropical and subtropical regions, pitaya doesn't produce fruit all year round. In tropical climates, plants can produce fruit 4 to 6 times a year (Pushpakumara *et al.*, 2005). However, in subtropical areas, while vegetative growth continues throughout the year, flower bud formation begins in May and harvesting takes place mainly during the summer and autumn months. Flowering tends to occur at similar times across plantations, leading to peak harvest periods. To manage this, storing the fruits under cold conditions for a certain period is believed to provide a significant advantage, balancing supply and demand and stabilizing prices. This is important because leaving the fruit at room temperature after harvest shortens its shelf life, reduces its market value. Some studies have investigated cold storage options, which are discussed below, but it is clear that storage conditions vary between studies. However, no research has examined how different training systems or deficit irrigation practices affect fruit storage. Furthermore, few studies have investigated the mechanisms behind the prolongation of post-harvest storage of pitaya fruit, and the process is unclear (Wang *et al.*, 2024). It is also not thoroughly examined the mechanisms of growth, development, and ripening of the fruit.

Earlier postharvest research on pitaya primarily focused on fruits harvested at different stages of peel color development, ranging from the initial appearance of color to full color (Razali *et al.*, 2016). To *et al.* (2002) emphasized that storage temperature is crucial for maintaining the postharvest quality of pitaya fruits. The importance of selecting the right storage temperature based on species and environmental conditions was also highlighted. Nerd *et al.* (1999) recommended storing pitaya fruits at 6 °C, while To *et al.* (2002) identified 5 °C as the optimal temperature for *Hylocereus undatus* grown in Vietnam. Zee et al. (2004) suggested that pitaya fruits can be stored at 8 °C for 25-30 days. Hoa *et al.* (2006) noted that *H. undatus* fruits, depending on their ripeness, can be stored at 5 °C. Freitas and Mitcham (2013), in a study evaluating storage temperatures of 5 °C, 7 °C, and 10 °C, recommended 5 °C to maintain fruit quality best and noted that this temperature is commonly used for export markets. However, Punitha *et al.* (2010) found that pitaya fruits should be stored at temperatures below 14 °C. Razali *et al.* (2016) observed that when fruits were stored at 1 °C and 4 °C for 20 days, weight loss increased, reaching up to 5.49%. Additionally, an increase in soluble solids content and a decrease in titratable acidity were noted, leading to a higher SSC/TA ratio. Wakchaure *et al.* (2023) similarly reported that pitaya fruits stored at 8 °C with 60-70% humidity for four weeks exhibited an increase in weight loss and soluble solids content while titratable acidity decreased.

Although there are no studies examining the combined effects of deficit irrigation and training systems in pitaya, it has been reported that reducing irrigation frequency increases soluble solids content while decreasing titratable acidity (Mizrahi *et al.*, 2007). The main postharvest losses in pitaya include mechanical, and chilling injury, decay, and weight loss (Nerd *et al.*, 1999; Wall and Khan, 2008; Chandran, 2010). After harvest, pitaya fruits are reported to begin to soften rapidly, with a sharp decline in malic acid content (Nerd *et* *al.*, 1999). Punitha et al. (2010) found that storing pitaya at temperatures above 20 °C leads to rapid softening, along with reductions in sugar and acid content.

As with pitaya cultivation, there is limited research on postharvest storage. As mentioned earlier, no studies have investigated the effects of different training systems and irrigation practices on postharvest storage. Moreover, studies on cold storage have shown variations in the recommended storage temperatures depending on the researchers. Therefore, the aim of this study was to investigate the effects of different training systems and deficit irrigation regimes on the postharvest storage period and associated changes in fruit quality of pitaya.

Materials and Methods

The experiment was conducted at the Alata Research Institute in Mersin, Türkiye, in 2022. Plants were grown under protected cultivation at Akdeniz University, Antalya, Türkiye, between 2020 and 2022. The 'Vietnamese Jaina' pitaya cultivar was used as plant material. It is one of the most widely grown cultivars in Türkiye. Plants were cultivated in 20-liter pots containing a mixture of 2/4 soil, 1/4 peat, and 1/4 perlite (Marques *et al.*, 2012). Pots were arranged in the greenhouse with a spacing of 2 meters between rows and 1.5 meters within the rows. In addition to the control (Pole system), two different training systems, T and Inverted U, were included in the study. Four irrigation regimes were tested: (1) FULL (DI100), where the total amount of irrigation water was applied uniformly to the plant root zone; (2) DI75, with 75% of the water applied in DI100; (3) DI50, with 50% of the DI100 water applied; and (4) DI25, with 25% of the DI100 water applied. Irrigation was applied using a drip irrigation system, with pipes placed in the root zone of the plants and octopus-type drippers delivering a flow rate of 2 l h^{-1}, ensuring one dripper per pot. Irrigation was scheduled every 10 days during winter, weekly in spring, and twice a week in summer. Fertilizer treatments were applied according to Chakma *et al.* (2014).

Fruits were harvested at stage 815 when the bracts on the fruit turned pink, and the fruit flesh had fully developed (Kishore, 2016). Previous studies have shown that the temperature and relative humidity of pitaya during storage varies between 5-16 °C and 65-95% respectively (Punitha *et al.*, 2010; Freitas and Mitcham, 2013; Lata *et al.*, 2024). The harvested fruits were stored at 10 °C and 80% relative humidity for 30 days (Punitha *et al.*, 2010; Lata *et al.*, 2024). Analyses were conducted at 10 days intervals during the storage period (Initial, 10th, 20th, and 30th day).

Investigation criteria

Titratable Acidity (TA)

For TA analysis, 5 ml of fruit juice was diluted with 100 ml of distilled water and titrated with 0.1 N NaOH to a pH of 8.2. Citric acid equivalents were calculated based on the TA (Cemeroğlu, 2010). In *Hylocereus* species, citric and malic acids are the primary compounds responsible for fruit acidity (Suh *et al.*, 2014).

Total Soluble Solids (TSS)

TSS was measured using a refractometer (Atago ATC-1E Model; Atago Co. Ltd., Tokyo, Japan), and expressed as °Brix.

Weight Loss (WL)

Weight loss was calculated at every analysing period throughout the storage using the formula given below and expressed as % Weight loss: [(Initial weight – last weight)/initial weight] ×100

Ascorbic acid (Vitamin C) content (mg kg^{-1})

A 5 g sample of fruit extract was transferred to a test tube and mixed with 5 ml of 2.5% m-phosphoric acid solution. The mixture was centrifuged at 2500 × g for 10 minutes at 4 °C. From the clear portion of the centrifuge tube, 0.5 ml was taken, and the volume was adjusted to 4 ml with 2.5% m-phosphoric acid solution. The mixture was passed through a 0.45 µm Teflon filter. The sample was analyzed for 15 minutes using an ODS3 column (column temperature 25 °C, 2% KH_2PO_4 (pH 2.4), isocratic flow, 0.6 ml min^{-1} flow rate, 10 µL injection volume) at 244 nm (Cemeroğlu, 2010).

Sugar content (glucose, fructose, sucrose) (g kg^{-1})

Fruit juice was diluted 1:2, passed through a 0.45 µm membrane filter, and prepared for analysis. The modified method of Bartolome et al. (1995) was used for high-performance liquid chromatography analysis. The flow rate was set at 1.3 ml min^{-1}, the mobile phase consisted of 80% acetonitrile + 20% pure water, the column temperature was 30 °C, and the analysis period was 25 minutes. Sugar content was determined using a refractive index detector based on peak area and compared with a standard calibration curve, with the amounts expressed in g kg^{1}.

Total phenolic content (mg GAE l^{-1})

Total phenolic content was determined using the Folin-Ciocalteu colorimetric method. A 0.5 ml sample of the extract was mixed with 2.5 ml of 0.2 N Folin-Ciocalteu reagent and 2 ml of sodium carbonate solution (75 g l^{-1}). The mixture was incubated at room temperature for 2 hours, and the absorbance was measured at 760 nm against methanol as a blank. Results were expressed as mg GAE l^{-1} (Akbulut *et al*., 2008).

DPPH antioxidant activity (mg TE l^{-1})

DPPH (2,2-Diphenyl-1-picrylhydrazyl) radical scavenging activity was determined based on the reduction of DPPH by antioxidant compounds in the extract, measured by the absorbance difference at 515 nm. A 0.1 ml sample of the extract was mixed with 3.9 ml of DPPH solution, and the mixture was incubated in the dark for 30 minutes. After incubation, the absorbance was measured at 515 nm. Results were expressed as antioxidant activity in mg TE l^{-1} (Akbulut *et al*., 2008).

The field experiment was laid out in a completely factorial block design with 3 replicates and 7 pots in each replicate. The cold storage experiment was conducted using a completely randomized design with three replications, each consisting of 10 fruits. The collected data were analyzed using JMP statistical software (JMP®, Version 7, SAS Institute Inc.; Cary, NC, 1989–2007; NC 27513-2414, USA). The Least Significant Difference (LSD) test was applied to compare treatment means.

Results

Titratable Acidity (TA) content (g citric acid [100 ml]$^{-1}$)

The effects of the interaction between the training system, irrigation regime, and storage period on TA content, as well as the effect of storage period alone, were found to be statistically significant. However, the individual effects of the training system and irrigation treatments were not statistically significant (Table 1). A decrease in TA content was observed throughout the storage period, ranging from 0.25 to 0.40 g citric acid [100 ml]$^{-1}$. The TA content varied depending on the training system and irrigation regimes, ranging from 0.32 to 0.34 g citric acid [100 ml]$^{-1}$ and from 0.31 to 0.33 g citric acid [100 ml]$^{-1}$, respectively.

Table 1. Effect of storage period, training systems, and irrigation treatments on TA content (%) (g citric acid [100 ml]$^{-1}$)

Training systems	Irrigation treatments	Storage period (Days)				Training system means	Irrigation treatment means
		0	10	20	30		
Control (Pole) System	FULL	0.34 a-k	0.30 c-m	0.36 a-j	0.22 i-m	0.34*	0.33[1*]
	DI75	0.40 a-f	0.29 c-m	0.29 c-m	0.19 lm		
	DI50	0.40 a-f	0.28 d-m	0.28 d-m	0.22 j-m		
	DI25	0.37 a-h	0.30 b-m	0.24 g-m	0.28 d-m		
T System	FULL	0.46 ab	0.31 b-m	0.31 b-m	0.29 c-m	0.33	0.31[2]
	DI75	0.37 a-i	0.33 b-k	0.34 a-k	0.27 d-m		
	DI50	0.34 a-l	0.37 a-i	0.31 c-m	0.30 d-m		
	DI25	0.47 a	0.31 b-m	0.36 a-j	0.20 k-m		0.31[3]
Inverted U System	FULL	0.42 a-d	0.36 a-k	0.30 c-m	0.26 f-m	0.32	
	DI75	0.40 a-e	0.31 b-m	0.30 c-m	0.27 e-m		
	DI50	0.44 abc	0.28 d-m	0.33 a-m	0.2 2 h-m		0.32[4]
	DI25	0.35 a-j	0.33 b-m	0.34 a-l	0.28 e-m		
Storage period means		0.40 A	0.31 B	0.31 BC	0.25 C		

LSD%5 storage period x training system x irrigation treatments: 0.151; LSD%5 storage period: 0.036

*: Not Significant

Means with different letters in the same column were significantly different: $P<0.05$

[1] FULL irrigation; [2] 75% deficit irrigation (DI75); [3] 50% deficit irrigation (DI50); [4] 25% deficit irrigation (DI25)

Total Soluble Solids (TSS) content (%)

The effects of training systems, storage period, and irrigation treatments, as well as their interactions, on TSS content were found to be statistically significant (Table 2). The results indicate that the TSS content fluctuated in all of the treatments to the 20th day and decreased at the 30th day of storage compared to the initial values. Among the training systems, the highest TSS content was recorded in the Pole (Control) system, while the lowest was observed in the T system. Regarding irrigation treatments, the lowest TSS content was found in the FULL irrigation regime, while the highest was observed in the 25% (DI25) deficit irrigation treatment.

Table 2. Effect of storage periods, training systems, and irrigation treatments on TSS content (%)

Training system	Irrigation treatments	Storage period (Days)				Training system means	Irrigation treatment means
		0	10	20	30		
Control (Pole) System	FULL	8.40 wxy	6.93 r-w	9.87 a	6.66 t-x	8.29 A	7.48 C[1]
	DI75	8.40 g-k	8.60 d-h	8.70 d-g	7.83 j-o		
	DI50	8.30 f-j	8.90 d-g	8.50 e-i	8.36 f-j		
	DI25	6.43 f-j	8.90 d-g	7.77 k-p	10.10 a		
T System	FULL	6.83 r-x	7.33 n-s	6.80 s-x	6.63 t-x	7.35 C	7.78 B[2]
	DI75	6.46 wxy	6.96 q-w	7.43 m-r	6.50 v-y		
	DI50	7.56 l-q	8.06 h-l	8.37 g-k	6.60 u-x		
	DI25	8.70 d-g	9.20 bcd	6.86 r-x	7-23 o-t		7.77 B[3]
Inverted U System	FULL	6.73 s-x	7.23 o-t	7.90 i-n	8.47 f-i	8.08 B	
	DI75	8.03 g-k	8.53 d-g	8.70 d-g	7.20 p-u		
	DI50	6.30 xy	6.80 s-x	9.66 ab	5.93 y		8.58 A[4]
	DI25	9.10 b-e	9.60 abc	10.13 a	9.00 c-f		
Storage period means		7.60 C	8.08 B	8.40 C	7.43 D		

LSD%5 storage period x training system x irrigation treatments: 0.1797; LSD%5 training systems: 0.341; LSD%5 irrigation treatments: 0.433; LSD%5 storage period: 0.433

Means with different letters in the same column were significantly different: $P<0.05$

[1] FULL irrigation; [2] 75% deficit irrigation (DI75); [3] 50% deficit irrigation (DI50); [4] 25% deficit irrigation (DI25)

Weight loss (%)

The effects of interaction, as well as all treatments, on weight loss were found to be statistically significant (Table 3). The findings showed that weight loss increased progressively with the storage period compared to initial values. Among the training systems, the highest weight loss was recorded in the T system, while the lowest was observed in the Inverted U system. In addition to this, weight loss decreased as the degree of deficit irrigation increased, with the most significant reduction observed under more restrictive irrigation regimes.

Table 3. Effect of storage periods, training systems, and irrigation treatments on weight loss (%)

Training system	**Irrigation treatments**	**Storage period (Days)**			**Training system means**	**Irrigation treatment means**
		10	**20**	**30**		
Control (Pole) System	FULL	1.80 k-r	2.58 d-k	2.93 b-i	2.49 A	
	DI75	2.36 e-n	2.18 f-p	4.14 a		2.35 AB[1]
	DI50	1.66 l-s	2.54 e-k	2.82 c-i		
	DI25	1.46 n-s	2.48 e-k	2.87 b-j		
T System	FULL	1.43 o-s	2.20 g-o	3.49 abc	2.36 AB	2.62 A[2]
	DI75	2.36 e-n	3.05 b-g	2.28 f-p		
	DI50	1.52 m-s	2.26 f-p	3.06 b-f		
	DI25	0.92 s	2.03 h-r	3.68 ab		2.25 B[3]
Inverted U System	FULL	1.42 prs	2.35 f-n	2.93 b-i	2.21 B	
	DI75	1.29 qrs	2.46 e-l	3.50 a-d		
	DI50	1.17 rs	2.03 h-r	3.19 b-e		2.18 B[4]
	DI25	1.77 k-s	2.11 k-p	2.31 f-o		
Storage period means		1.52 C	2.35 B	3.10 A		

LSD%5 storage period x training system x irrigation treatments: 0.773; LSD%5 training systems: 0.061; LSD%5 irrigation treatments: 0.071; LSD%5 storage period: 0.071

Means with different letters in the same column were significantly different: $P<0.05$

[1] FULL irrigation; [2] 75% deficit irrigation (DI75); [3] 50% deficit irrigation (DI50); [4] 25% deficit irrigation (DI25)

Ascorbic acid content ($mg\ kg^{-1}$)

The effects of interaction, storage period, and training systems on ascorbic acid content were found to be statistically significant, except for irrigation treatments (Table 4). The results showed a decrease in ascorbic acid content as storage time increased compared to initial values. Among the training systems, the highest ascorbic acid content was observed in the Pole (Control) system, while the lowest was recorded in the Inverted U system. The ascorbic acid content values determined according to irrigation regimes (FULL, DI75, DI50 and DI25) varied between 34.6 and 36.3 ($mg\ kg^{-1}$). However, this variation was not found to be statistically significant.

Table 4. Effect of storage periods, training systems, and irrigation treatments on ascorbic acid content (mg kg^{-1})

Training systems	Irrigation treatments	Storage period (Days)				Training system means	Irrigation treatment means
		0	10	20	30		
Control (Pole) System	FULL	42.0 ab	34.3 b	31.1 b	36.2 ab	37.0 A	34.6^{1*}
	DI75	40.0 ab	34.3 b	35.7ab	31.9 b		
	DI50	44.5 ab	34.1 b	36.4 ab	31.2 b		
	DI25	53.2 a	34.8 b	41.0 ab	31.2 b		
T System	FULL	37.2ab	33.4 b	32.1 b	33.0 b	34.6 AB	34.7^{2}
	DI75	37.9 ab	33.5 b	32.8 b	33.1 b		
	DI50	42.1 ab	34.2 b	28.2 b	34.9 b		
	DI25	41.0 ab	34.3 b	29.6 b	35.8 ab		35.1^{3}
Inverted U System	FULL	33.6 b	36.1 ab	31.6 b	34.2 b	33.9 B	
	DI75	33.7 b	37.3 ab	31.8 b	34.8 b		36.3^{4}
	DI50	35.6 ab	32.7 b	32.1 b	34.6 b		
	DI25	35.5 ab	33.1 b	32.6 b	33.1 b		
Storage period means		39.7 A	34.3 B	33.7 B	32.9 B		

LSD%5 storage period x training system x irrigation treatments: 4.14; LSD%5 training systems: 2.69; LSD%5 storage period: 3.41

*: Not Significant

Means with different letters in the same column were significantly different: P<0.05

[1]FULL irrigation; [2]75% deficit irrigation (DI75); [3]50% deficit irrigation (DI50); [4]25% deficit irrigation (DI25)

Sugar content (fructose, glucose, and sucrose) (g kg^{-1})

The effects of interaction and storage period on fructose content were found to be statistically significant, while the effects of training systems and irrigation treatments were not significant (Table 5). The sugar content of the fruit fluctuated in all of the treatments throughout the storage. By the 30th day of storage, fructose content showed a decrease compared to the initial values. Fructose content varied based on training systems and irrigation treatments, ranging between 15.6 and 17.8 g kg^{-1} for training systems and 16.1 and 17.4 g kg^{-1} for irrigation treatments.

Table 5. Effect of storage periods, training systems, and irrigation treatments on fructose content (g kg^{-1})

Training systems	Irrigation treatments	Storage period (Days)				Training system means	Irrigation treatment means
		0	10	20	30		
Control (Pole) System	FULL	23.1 abc	9.9 bc	31.3 a	12.3 abc	17.1*	17.3^{1*}
	DI75	22.1 abc	8.6 c	31.0 ab	11.3 abc		
	DI50	19.6 abc	11.2 abc	25.3 abc	10.7 abc		
	DI25	14.7 abc	9.3 c	25.8 abc	06.8 c		
T System	FULL	25.8 abc	14.4 abc	19.1 abc	11.2 abc	17.8	17.4^{2}
	DI75	24.7 abc	14.2 abc	22.1 abc	10.8 abc		
	DI50	22.8 abc	14.5 abc	20.6 abc	11.4 abc		
	DI25	23.5 abc	11.8 abc	25.6 abc	11.7 abc		16.1^{3}
Inverted U System	FULL	10.5 abc	24.9 abc	6.5 c	18.8 abc	15.6	
	DI75	9.9 abc	26.1 abc	9.5 c	18.1 abc		16.5^{4}
	DI50	15.5 abc	18.8 abc	9.7 c	12.5 abc		
	DI25	22.2 abc	18.0 abc	16.6 abc	11.4 abc		
Storage period means		19.6 A	15.1 B	20.3 A	12.2 B		

LSD%5 storage period x training system x irrigation treatments: 21.5; LSD%5 storage period: 4.4

*: Not Significant

Means with different letters in the same column were significantly different: P<0.05

[1]FULL irrigation; [2]75% deficit irrigation (DI75); [3]50% deficit irrigation (DI50); [4]25% deficit irrigation (DI25)

The effects of interaction and irrigation treatments on glucose content were not statistically significant, while the effect of training systems was found to be significant (Table 6). Glucose content increased throughout the storage until the 20th day, and a decrease was observed at the 30th day of storage. Among the training systems, the highest glucose content was recorded in the T system (54.0 g kg^{-1}), while the lowest (48 g kg^{-1}) was found in the Control system. On the contrary, glucose content was not affected by irrigation system.

Table 6. Effect of storage periods, training systems, and irrigation treatments on glucose content (g kg^{-1})

Training system	**Irrigation treatments**	**Storage period (Days)**				**Training system means**	**Irrigation treatment means**
		0	**10**	**20**	**30**		
Control (Pole) System	FULL	50.8*	45.4	65.3	48.8	48.0 B	52.1[1]*
	DI75	46.6	42.5	55.2	51.0		
	DI50	43.1	48.2	49.0	47.6		
	DI25	42.5	36.6	53.0	42.4		
T System	FULL	54.4	56.7	57.1	55.5	54.0 A	51.3[2]
	DI75	49.0	51.0	62.4	52.8		
	DI50	50.3	51.2	66.0	49.2		
	DI25	52.6	43.8	65.1	46.8		50.5[3]
Inverted U System	FULL	38.8	59.2	42.2	51.3	51.0 AB	
	DI75	40.3	64.4	43.0	57.2		51.0[4]
	DI50	46.8	58.9	42.5	53.2		
	DI25	54.0	60.3	49.4	55.2		
Storage period means		47.4 B	51.5 AB	54.2 A	50.9 AB		

LSD%5 storage period x training system x irrigation treatments: LSD%5 training systems: 5.6; LSD%5 storage period: 6.4

*: Not Significant

Means with different letters in the same column were significantly different: P<0.05

[1]FULL irrigation; [2]75% deficit irrigation (DI75); [3]50% deficit irrigation (DI50); [4]25% deficit irrigation (DI25)

Similar to glucose, the effects of interaction and irrigation treatments on sucrose content were not statistically significant, whereas the effects of storage period and training systems were significant (Table 7).

Table 7. Effect of storage periods, training systems, and irrigation treatments on sucrose content (g kg^{-1})

Training systems	**Irrigation treatments**	**Storage period (Days)**				**Training system means**	**Irrigation treatment means**
		0	**10**	**20**	**30**		
Control (Pole) System	FULL	40.6*	36.3	52.2	39.0	38.4 B	41.7[1]*
	DI75	37.3	34.0	44.2	40.8		
	DI50	34.5	38.6	39.2	38.1		
	DI25	34.0	29.3	42.3	33.9		
T System	FULL	43.5	45.3	45.7	44.4	43.2 A	41.0[2]
	DI75	39.2	40.8	49.9	42.2		
	DI50	40.2	41.0	52.8	39.4		
	DI25	42.1	35.1	52.1	37.4		40.4[3]
Inverted U System	FULL	31.0	47.4	33.8	41.0	40.8 AB	
	DI75	32.2	51.5	34.4	45.8		40.1[4]
	DI50	37.5	47.1	34.0	42.6		
	DI25	43.2	48.2	39.5	44.1		
Storage period means		37.9 B	41.2 AB	43.3 A	40.7 AB		

LSD%5 storage period x training system x irrigation treatments: LSD%5 training systems: 4.51; LSD%5: storage period 5.1

*: Not Significant

Means with different letters in the same column were significantly different: P<0.05

[1]FULL irrigation; [2]75% deficit irrigation (DI75); [3]50% deficit irrigation (DI50); [4]25% deficit irrigation (DI25)

Sucrose content increased throughout the storage compared to initial values but a decrease was recorded at the 30th day of storage. Regarding training systems, sucrose content was lowest in the Control system, as observed with glucose. Unlike training systems, irrigation regimes did not affect sucrose content.

Total phenolic content (mg GAE l^{-1})

The effects of all treatments, and interactions on total phenolic content were found to be statistically significant (Table 8). The highest total phenolic content was recorded on the 20th day of storage (240.5 mg GAE l^{-1}), while the lowest was observed on the 30th day (124.2 mg GAE l^{-1}) of storage. Total phenolic content, based on training systems, ranged from 175.1 mg GAE l^{-1} to 196.4 mg GAE l^{-1}, with the highest value recorded in the Inverted U system. Regarding irrigation treatments, the lowest phenolic content was observed under FULL irrigation (168.0 mg GAE l^{-1}), while the highest content was recorded in the DI50 irrigation treatment at 198.2 mg GAE l^{-1}.

Table 8. Effect of storage periods, training systems, and irrigation treatments on total phenolic content (mg GAE l^{-1})

Training system	Irrigation treatments	Storage period (Days)				Training system means	Irrigation treatment means
		0	10	20	30		
Control (Pole) System	FULL	161.2 i-m	145.5 j-m	278.9 c-f	116.2 lm	193.3 A	168.0 B^1
	DI75	277.9 c-f	280.9 c-f	270.0 def	133.8 klm		
	DI50	131.9 lm	264.2 def	221.0 e-i	107.3 m		
	DI25	112.2 lm	213.2 f-j	251.4 d-g	127.9 lm		194.3 A^2
T System	FULL	119.1 lm	159.3 i-m	360.3 ab	111.3 lm	175.1 B	
	DI75	134.8 klm	264.2 def	163.2 i-m	144.6 j-m		
	DI50	249.5 a-g	172.0 h-m	185.8 g-l	98.5m		
	DI25	238.7 d-h	131.9 lm	168.1 h-m	100.5 m		198.2 A^3
Inverted U System	FULL	171.0 h-m	118.1 lm	145.6 j-m	115.2 lm	196.4 A	
	DI75	350.5 bc	107.3 m	104.4 m	99.5 m		193.6 A^4
	DI50	293.6 b-e	137.2 klm	309.3 bcd	208.3 f-k		
	DI25	290.1 b-e	137.7 klm	427.9 a	127.0 lm		
Storage period means		210.9 B	178.5 C	240.5 A	124.2 D		

LSD%5 storage period x training system x irrigation treatments: 15.364; LSD%5 training systems: 17.22; LSD%5 irrigation treatments 18.05; LSD%5 storage period: 37.04

Means with different letters in the same column were significantly different: $P<0.05$

^{1}FULL irrigation; ^{2}75% deficit irrigation (DI75); ^{3}50% deficit irrigation (DI50); ^{4}25% deficit irrigation (DI25)

Antioxidant activity (mg TE l^{-1})

The effects of all treatments and interactions on antioxidant activity were found to be statistically significant, similar to total phenolic content (Table 9). The lowest antioxidant activity was recorded on day 0 of storage at 21.4 mg TE l^{-1}, while the highest was observed on day 20 at 31.1 mg TE l^{-1}. Antioxidant activity values varied between 22.6 mg TE l^{-1} and 31.2 mg TE l^{-1} regarding the training systems, with the highest value recorded in the Inverted U system. Regarding irrigation treatments, the lowest antioxidant activity was observed in the DI75 irrigation treatment at 16.8 mg TE l^{-1}, while the highest was recorded in the DI25 treatment at 31.5 mg TE l^{-1}.

Table 9. Effect of storage periods, training systems, and irrigation treatments on antioxidant activity (mg TE l^{-1})

Training system	Irrigation treatments	Storage period (Days)				Training system means	Irrigation treatment means
		0	10	20	30		
Control (Pole) System	FULL	26.2 g-m	26.9 g-l	43.5 b-f	10.6 o-s	25.2 B	28.2 AB[1]
	DI75	20.3 j-q	20.2 jq	18.1 k-r	1.2 s		
	DI50	16.2 l-r	57.9 a	25.0 g-m	6.2 rs		
	DI25	19.6 k-r	42.6 b-f	53.0 ab	15.8 l-r		
T System	FULL	19.8 k-q	52.4 ab	37.0 c-g	18.1 k-r	22.6 C	16.8 B[2]
	DI75	14.6 l-s	12.8 m-s	12.8 m-s	25.0 g-m		
	DI50	18.9 k-r	6.9 qrs	24.6 g-n	20.3 j-q		28.4 AB[3]
	DI25	13.9 l-s	11.2 n-s	35.7 d-h	37.5 c-g		
Inverted U System	FULL	18.4 k-r	30.2 f-k	9.1 p-s	49.0 a-d	31.2 A	
	DI75	21.0 ı-p	23.0 h-o	15.6 l-r	15.4 l-r		31.5 A[4]
	DI50	34.3 e-ı	34.8 e-h	49.6 abc	45.7 a-e		
	DI25	33.4 e-j	35.6 e-h	48.6 a-d	35.5 d-h		
Storage period means		21.4 B	29.6 A	31.1 A	23.4 B		

LSD%5 storage period x training system x irrigation treatments: 26.07: LSD%5 training systems: 2.30; LSD%5 irrigation treatments: 6.28; LSD%5 storage period: 6.28

Means with different letters in the same column were significantly different: P<0.05

[1]FULL irrigation; [2]75% deficit irrigation (DI75); [3]50% deficit irrigation (DI50); [4]25% deficit irrigation (DI25)

Discussion

This study evaluated the effects of different training systems (Control (Pole), T system, and Inverted U) and irrigation regimes (FULL, DI75, DI50, and DI25) on pitaya fruits stored at 10 °C and 80% relative humidity for 30 days. Storing pitaya at temperatures above 20 °C results in rapid softening and loss of both sugars and acidity (Punitha *et al.*, 2010). Therefore, fruit is typically stored at temperatures of 14 °C or lower to slow these changes. However, storing the fruit at temperatures below 5 °C can cause chilling injury. The ideal storage temperature can be changed according to the genetic variety and growing environment to effectively preserve the quality of pitaya fruit after harvest (Razali *et al.*, 2016). Nerd *et al.* (1999) stated that pitaya fruit (*Hylocereus undatus* and *Hylocereus polyrhizus*) grown in Israel should be stored at 10 °C to decrease quality loss and avoid chilling injury. The storage temperature was chosen based on the recommendations of Nerd *et al.* (1999). According to our results, titratable acidity (TA) decreased after the 20th day of storage, with no significant effects of training systems or irrigation regimes. TA values in this study were in agreement with those reported by Razali *et al.* (2016) and Wakchaure et al. (2023), who also noted a decline in TA content over time. The values were comparable to earlier studies of TA ranging between 0.30% and 0.36% (Sornyatha and Anprung, 2009; Arévalo-Galarza and Ortíz-Hernández, 2004; Martínez Chávez, 2011).

Total soluble solids (TSS) content varied with storage period, training systems, and irrigation treatments. A decrease in TSS was observed after the 20th day of storage, similar to the trend in TA. The highest TSS content was found in the Control system, possibly due to greater light exposure. Among irrigation treatments, DI25 resulted in the highest TSS content, likely due to reduced water availability and increasing sugar concentration. Razali *et al.* (2016) and Wakchaure *et al.* (2023) also reported an increase in TSS during the early storage period, consistent with this study's findings.

Postharvest storage at room temperature negatively affects weight loss, decay, external appearance, and quality parameters compared to cold storage (Nerd *et al.*, 1999). However, weight loss increased towards the end of cold storage as well. The highest weight loss occurred in the Control system, while the lowest was found in the Inverted U system. Among irrigation treatments, DI25 had the lowest weight loss, with findings similar to those reported by Nerd *et al.* (1999) and Wakchaure *et al.* (2023), who observed an increase in weight loss during storage.

Ascorbic acid content decreased with storage time. The highest ascorbic acid content was recorded in the Control system and the lowest in the Inverted U system. Irrigation treatments did not significantly affect ascorbic acid content. The values differed from those reported by Jamilah *et al.* (2011), who found ascorbic acid content to be 8-9 mg/100 g. These differences could be due to variations in cultivar, ecological conditions, irrigation regimes, and training systems.

Fructose, glucose, and sucrose contents fluctuated during storage, depending on the training systems and storage period. Irrigation treatments did not significantly affect sugar content. Glucose was the dominant sugar, followed by sucrose and fructose. A decline in all sugar types was observed after the 20th day of storage, similar to TA and TSS. Among training systems, the Control system had lower glucose and sucrose contents compared to the others. Sugar content in pitaya varies based on the maturation stage and harvest season, with higher levels observed in summer and autumn (Nomura *et al.*, 2005). Hua *et al.* (2018) also reported glucose as the dominant sugar, aligning with this study's findings. Öziyci *et al.* (2024) noted that sugar content differs across cultivars, including red-peeled white-fleshed and red-peeled red-fleshed varieties.

Total phenolic content fluctuated over the storage period, with the lowest value recorded on the 30th day. The Control and Inverted U systems were in the same statistical group in terms of phenolic content. Most irrigation treatments, except FULL, also belonged to the same statistical group. Öziyci *et al.* (2024) reported significant differences in phenolic content across different pitaya cultivars, with values ranging from 38.59 mg GAE/L to 621.06 mg GAE/L, the lowest found in the Vietnamese Jaina cultivar. The differences in total phenolic content observed in this study could be attributed to variations in training systems and irrigation regimes.

Antioxidant activity varied with storage period, training systems, and irrigation treatments. A decline in antioxidant activity was observed after the 20th day of storage. The highest antioxidant activity was recorded in the T system, and among irrigation treatments, DI25 had the highest value. These results are consistent with those reported by Öziyci *et al.* (2024) for the 'Vietnamese Jaina' cultivar.

Conclusions

The experimental results show that the postharvest quality of the Vietnamese Jaina pitaya cultivar can be effectively maintained during the storage at 10 °C and 80% relative humidity for up to 20 days, without significant quality loss under all training systems and with both 75% deficit irrigation (DI75) and full irrigation (FULL) regimes. Both deficit irrigation (DI75) and full irrigation (FULL) regimes had no significant effect on fruit quality under these conditions However, towards the end of storage, fruit quality declined, particularly in the D25 irrigation regime, due to smaller fruit size compared to the D75 and FULL irrigation treatments.

In conclusion, both the DI75 and FULL irrigation regimes effectively preserve fruit quality, with the choice between them depending on water availability and resource management priorities. On the other hand, the training system does not significantly affect fruit quality and can be selected based on practical factors such as ease of management and labor needs.

Authors' Contributions

Conceptualization: MÜ, LA, HG and HK. Data curation: MÜ, LA, HG and HK. Formal analysis: MÜ, LA, HG and HK. Project administration: HG and HK. Writing - original draft: MÜ, LA, HG and HK. Writing - review and editing: MÜ, LA, HG and HK. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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