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Economic Indices for the Application of Irrigation to Enhance Cactus Pear Fruit Yield

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Authors' contributions

This work was carried out in collaboration between both authors. Author BIST performed study methodology, formal analysis, wrote original draft of the manuscript, reviewed, edited and supervised the study. Author JAZ helped in conceptualization, method preparation, did formal analysis, data curation, investigatigate the work, resource preparation, wrote original draft, reviewed, edited and supervised the study, helped in project administration and funding acquisition. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: Cactus pear cultivation for fruit production is under rainfed conditions, mainly. Hence, irrigation uses for this purpose is expensive in arid and semi-arid agricultural lands**.** The objective of this study was to derive agro-economic indicators associated with supplemental irrigation to improve fruit yield of commercial cactus pear cultivars grown in a semiarid agroecosystem of Mexico.
Study Design: The irrigation treatments tested were fully irrigated (FI) and supplemental irrigation (SI), with non-irrigated as a control (NI).
Place and Duration of Study: The experiment was set up at the Campo Experimental Zacatecas, Calera, Zacatecas, Mexico from 2011 to 2013.
Methodology: Five-year-old cactus pear plants of 'Cristalina' (*O. albicarpa* Scheinvar; white-pulped fruit) and 'Roja Lisa' [*O. ficus-indica* (L.) Mill.; red-pulped fruit] were included. The experiment was conducted in a split-block design. There were three blocks; each included both cultivars, randomly allocated to each irrigation treatment. The response variables were: fruit yield (FY), cultivation costs (CC), gross return (GR), net return (NR), benefit-cost ratio (BC), irrigation use efficiency (IUE),

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gross water productivity (GWP), net water productivity (NWP), labor productivity (LP), break-even-point (BEP), and credit vulnerability (CV).
Results: In all years but 2013, FI 'Cristalina' plants had the highest CC, reflected in their greater GR and NR; however, BC values were similar between SI and FI plants or greater in SI plants for 2013. Therefore, SI plants had the highest IUE, GWP, NWP, LP, EP, and equal or greater credit vulnerability than FI plants. The NI plants produced positive values for BEP and CV. The economic indices for 'Roja Lisa' were similar to those of 'Cristalina'.
Conclusion: The SI treatment produced the best agricultural economic indices and it is also a feasible water-saving irrigation strategy for cactus pear cultivation in semiarid agroecosystems worldwide.

Keywords: Opuntia spp.*; water productivity; benefit-cost ratio; labor productivity.*

1. INTRODUCTION

Global warming is a human-induced phenomenon that gradually endangers food security in different aspects of livestock [1] and agricultural production systems [2]. This situation is expected to be more pronounced in developing countries [1,3] in particular, those located in tropical, arid, and semi-arid regions, where agricultural activities are the main source of employment and income and where high temperatures are experienced already [4]. In these regions, the increased temperatures will raise water loss via evapotranspiration and intensify plant water stress, leading to poor harvests [2,5]. In addition to extreme temperatures, low and erratic precipitation, limited water availability, available agricultural practices in arid and semiarid agroecosystems are also limited [6]. However, there are xerophytic plants well adapted to such environments with remarkable socio-economic importance, such as cactus pear (*Opuntia* spp.) [7]. Cactus pear is highly efficient in water use because this plant uses a photosynthetic process known as crassulacean acid metabolism [8]. This plant species is grown for purposes such as animal feed, human consumption, and biogas production, among other uses [9].

Cactus pear, as a fruit crop, is cultivated mainly under rainfed conditions. Regardless of water scarcity and its cost for agricultural purposes, in some countries, irrigation has been adopted to enhance fruit yield productivity of cactus pear [10,11,12,13,14]. In semiarid highlands of Mexico, fruit yield from irrigated plants may be enhanced, on average, by 118% over non-irrigated plants (rainfed cultivation) [15].

Recently, supplemental irrigation was tested in 'Dalia Roja' cactus pear (a non-commercial cultivar) as a water-saving irrigation strategy [16]. Fruit yield increased in irrigated plants, up to 20% greater than in non-irrigated plants. The supplemental irrigation strategy used 52% less water than fully irrigated plants [17]. Because water is scarce and expensive for irrigation, an economic evaluation is needed. Hence, this study derived agro-economic indicators associated with supplemental irrigation to improve fruit yield in commercial cactus pear cultivars grown in a semiarid agro ecosystem. We hypothesized that supplemental irrigation would have economic advantages over either full irrigated or non-irrigated plants.

2. MATERIAL AND METHODS

2.1 Experimental Site Description

The experiment was set up at the Campo Experimental Zacatecas, Calera, Zacatecas, México (lat. 22°54' N, long. 102°39' W, elevation 2,197 m) from 2011 to 2013. The annual mean temperature of the experimental site is 14.6 °C and it averages 416 mm annual rainfall, with 75% occurring between July and October. Except for the 2013 growing season, the previous two growing seasons were the driest seasons during the experimental period for both cactus pear cultivars. 'Roja Lisa' received precipitation of 24 mm for 2011, 55 mm for 2012, and 180 for 2013. The corresponding values for 'Cristalina' were: 50, 86, and 213 mm, respectively. The average annual pan evaporation is 1,609 mm. The orchard soil has a loam texture with 1.73% organic matter content at pH 7.75. The soil physical parameters at 30 cm soil depth were: 0.28 field capacity (FC) and 0.14 m^3 m^{-3} permanent wilting point (PWP).

2.2 Plant Material and Orchard Management

Five-year-old cactus pear plants (*Opuntia* spp.) of cultivars used for fruit production were studied. They were 'Cristalina' (*O. albicarpa* Scheinvar; white-pulped fruit) and 'Roja Lisa' [*O. ficus-indica* (L.) Mill.; red-pulped fruit]. The last cultivar bears

earlier-maturing fruit than 'Cristalina'. Plants were spaced at 4 x 3 m between and within the row, respectively, and trained into an open vase system. Plants were handled using local commercial cultivation practices. To minimize erosion by water and wind, orchard soil between plant rows was planted with a mixture of native grasses that were mowed periodically.

2.3 Treatments and Experimental Design

The irrigation treatments were full irrigation (FI), where water depth was applied weekly to bring FC back to 0.28 m^3 m^{-3}; supplemental irrigation (SI), where water depth was supplied to restore FC every time soil water content (θ) dropped to 0.14 m^3 m^{-3}; and no irrigation (NI) as the rainfed control. During the experimental period, θ was verified at a soil depth of 30 cm in all treatments before and 24 h after each irrigation episode using time-domain reflectometry (TDR, Mini-Trase System, Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Irrigation requirements were estimated weekly using a soil-water balance [17].

The experiment was conducted in a split-block design. There were three blocks; each included both cultivars, randomly allocated to each irrigation treatment (six experimental units per block). Nine cactus pear plants per cultivar comprised each experimental unit.

2.4 Basic Response Variables

The amount of water applied for each treatment was estimated each growing season by a soil water balance at each irrigation event for each cultivar [17]. Fruit yield was collected from the two central plants. This occurred from July 16 to August 26 in 2011, from July 16 to September 18 in 2012, and from August 3 to September 10 in 2013. Fruit from each plant per cultivar was harvested separately and graded by equatorial diameter (ED, cm) into Grade 1 to Grade 5. Grade 1 fruit had ED > 7.0 cm; Grade 2 fruit, ED between 6.0 and 7.0 cm; Grade 3 fruit, ED between 5.0 to 5.9 cm; Grade 4 fruit, ED between 4.1 to 4.9 cm; and Grade 5 fruit shorter than 4.0 cm. Fruits from each plant were counted and weighed and the total mass was the gross yield.

2.5 Fixed Economic Practices of the Orchard Management

This section included the supplementary agricultural costs associated with using mineral fertilizers, chemicals, gasoline, diesel fuel, and labor costs applied to the orchard each growing season. This included cladode pruning (winter and late spring pruning), reproductive bud thinning, pest and disease control, weed control (mechanical and chemical), fertigation (NPK mineral fertilizers), hand-harvesting, delivery to the packing area, packing and handling (glochid removal, grading, and packing). Unlike other irrigation studies [18], this one included labor costs, number of irrigation hours, the cost of electrical energy consumption (kilowatt-hour), and the costs of groundwater extraction and application.

2.6 Agro-Economic Indices

Using the information from the last two sections, we derived the following agro-economic indices: cultivation costs (CC) in USD/ha; grower's gross returns as grower's gross incomes (GGI) per t in USD/ha; the grower's net income (GNI) per t in USD/ha; the benefit-cost (BC) ratio as GGI/CC (when this ratio is greater than one, it means a profit per unit input) [19]. The irrigation use efficiency (IUE) as the ratio of fruit yield produced (kg) per amount water applied (mm) during each growing season per treatment per cultivar; gross water productivity (GWP) as the ratio of GGI to the amount of water applied during each growing season per irrigation treatment per cultivar; and net water productivity (NWP) as the ratio of GNI to the amount of water applied during each growing season per irrigation treatment per cultivar [17]. Other economic indices were labor productivity (LP), break-even point (BEP), and credit vulnerability (CV) [20,21]. The LP is the ratio of the number of manpower (hours) over fruit yield (t) produced per ha. The BEP is a dimensionless index generated between CC and the value per ton (t) of fruit yield. The CV is a dimensionless index ratio of fruit yield (t ha^{-1}) over BEP. So, an index greater than one implies that cactus pear growers can have access to credit for agricultural inputs such as fertilizers, pesticides, irrigation, and harvest [22]; otherwise, farmers will not qualify to apply for this kind of credit.

2.7 Data Analysis

The data set was analyzed and presented descriptively by cactus pear cultivar.

3. RESULTS

3.1 Cultivation Costs

Over three years, the average cultivation costs for 'Cristalina' cactus pear were ≈ 35% and 44%

greater with supplemental irrigated (SI) and fully irrigated (FI) plants than in non-irrigated (NI) plants, respectively. The corresponding values for 'Roja Lisa' cactus pear were 34% and 39% for SI and FI plants, respectively (Table 1).

3.2 Returns and Benefit-Cost

Gross returns for 'Cristalina' cactus pear were similar between SI and FI plants, at 62% (SI) and 64% (FI) greater than for NI plants. The corresponding values for 'Roja Lisa' were ≈ 91% and 67% greater for SI and FI plants, respectively (Table 1). Thus, net returns increased by ≈ 102% and 92% for SI and FI 'Cristalina' cactus pears, respectively; while in 'Roja Lisa', the increases were ≈ 441% and 186% for SI and FI plants, respectively. All these values were reflected in greater benefit-costs or profitability, for SI and FI 'Cristalina' plants than for NI 'Cristalina': ≈ 63%, 97%, and 80% for NI, SI, and FI plants, respectively. A similar pattern was observed in 'Roja Lisa', but the profitability was less than for 'Cristalina' at ≈ 13%, 53%, and 30% for NI, SI, and FI plants, respectively (Table 2).

3.3 Irrigation and Water Productivity

Our primary objective was to test SI as a water-saving strategy to address physical water scarcity and high-water costs for agricultural activities in arid and semi-arid regions. This goal was achieved with the calculated water use efficiencies, where 'Cristalina' SI plants showed greater water use efficiency than FI and NI plants. This also increased gross water productivity and net water productivity in SI plants. Similar trends were seen in 'Roja Lisa' plants (Table 3).

3.4 Labor Productivity, Break-Even Point and Credit Vulnerability

The number of hours invested to produce a t of fruit yield, or labor productivity, was similar between SI and FI 'Cristalina' plants, at ≈ 91% and 89% of the labor productivity of NI plants, respectively. The values for 'Roja Lisa' were ≈ 93% and 118% of the value for NI plants for SI and FI plants, respectively. The break-even point, as the ratio of cultivation costs to the value per t of fruit yield, was the greatest in SI and FI plants for both cactus pear cultivars. As the index of credit vulnerability was greater than one with all three irrigations treatments in both cactus pear cultivars, a cactus pear grower could apply for agricultural credit. However, in both cactus pear cultivars, SI and FI plants produced higher positive indices than NI plants (Table 4).

4. DISCUSSION

The development of applied technologies for agricultural activities should have three possible outputs: 1) cost decline, 2) yield improvement, and 3) a mixture of the first two: produce greater yields at less cost [23]. However, the shift from traditional agricultural inputs toward modern inputs such as irrigation (among other technologies) deserves an economic analysis of its profitability [24]. So, according to our objective, the application of supplemental irrigation generated similar fruit yields to full irrigation in both cactus pear cultivars (Table 1), and therefore, similar economic indices, in terms of gross and net returns (Table 2). However, despite irrigation costs involved (e.g., water, electricity, and operation costs), the estimated benefit-cost ratio for supplemental irrigation was, on average, higher than for full irrigation in both

Table 1. Influence of irrigation treatments on cultivation cost (USD ha^{-1}) of 'Cristalina' and 'Roja Lisa' cactus pear cultivars. SEM is the standard error of the mean

	Growing seasons			
Cultivar/ irrigation treatments	**2011**	**2012**	**2013**	**Mean (± SEM)**
'Cristalina'				
Non-irrigated	793	1,157	944	964 ± 106
Supplemental irrigation	967	1,597	1,339	1,301 ± 183
Full irrigation	1,072	1,821	1,279	1,391 ± 223
'Roja Lisa'				
Non-irrigated	738	833	808	793 ± 29
Supplemental irrigation	872	1,018	1,295	1,061 ± 124
Full irrigation	906	1,156	1,242	1,101 ± 101

Table 2. Influence of irrigation treatments (IT) on grower's gross returns (GGR), grower's net returns (GNT), and benefit-cost ratios (B:C) of cactus pear cultivation. SEM is the standard error of the mean

	Gross returns (USD ha^{-1})				Net returns (USD ha^{-1})				B:C ratio			
Cultivar/IT	**2011**	**2012**	**2013**	**Mean (± SEM)**	**2011**	**2012**	**2013**	**Mean (± SEM)**	**2011**	**2012**	**2013**	**Mean (± SEM)**
'Cristalina'												
Non-irrigated	986	2,372	1,513	1,624 ± 404	193	1,215	570	659 ± 298	1.2	2.1	1.6	1.63 ± 0.3
Supplemental irrigation	1,356	3,779	2,761	2,632 ± 703	389	2,183	1,422	1,331 ± 520	1.4	2.4	2.1	1.97 ± 0.3
Full irrigation	1,531	4,330	2,106	2,656 ± 853	460	2,509	827	1,265 ± 631	1.4	2.4	1.6	1.80 ± 0.3
'Roja Lisa'												
Non-irrigated	722	1,025	936	894 ± 89	-16	192	128	101 ± 61	1.0	1.2	1.2	1.13 ± 0.2
Supplemental irrigation	986	1,576	2,574	1,712 ± 463	114	558	1,279	651 ± 339	1.1	1.5	2.0	1.53 ± 0.3
Full irrigation	845	1,668	1,966	1,493 ± 335	-61	512	724	392 ± 234	0.9	1.4	1.6	1.30 ± 0.2

Table 3. Influence of irrigation treatments (IT) on irrigation water productivity (IUE), gross water productivity (GWP), and net water productivity (NWP) of cactus pear cultivation. SEM is the standard error of the mean

	IUE (kg m^{-3})				GWP (USD m^{-3})				NWP (USD m^{-3})			
Cultivar/IT	**2011**	**2012**	**2013**	**Mean (± SEM)**	**2011**	**2012**	**2013**	**Mean (± SEM)**	**2011**	**2012**	**2013**	**Mean (± SEM)**
'Cristalina'												
Non-irrigated	—	—	—	—	—	—	—	—	—	—	—	—
Supplemental irrigation	5.2	16.9	10.1	10.7 ± 3.4	2.6	2.6	1.6	2.3 ± 0.3	0.3	1.5	0.8	0.87 ± 0.35
Full irrigation	3.1	8.5	3.6	5.1 ± 1.7	1.3	1.3	0.6	1.1 ± 0.2	0.2	0.8	0.2	0.40 ± 0.20
'Roja Lisa'												
Non-irrigated	—	—	—	—	—	—	—	—	—	—	—	—
Supplemental irrigation	4.7	5.9	9.4	6.7 ± 1.4	0.9	0.9	1.5	1.1 ± 0.2	0.1	0.3	0.7	0.37 ± 0.18
Full irrigation	1.9	3.3	3.3	2.8 ± 0.5	0.5	0.5	0.5	0.5 ± 0.0	0.0	0.2	0.2	0.13 ± 0.07

Table 4. Influence of irrigation treatments (IT) on labor productivity (LP), break-even point (BEP), and credit vulnerability of cactus pear cultivation. SEM is the standard error of the mean

Cultivar/IT	LP (h t^{-1} ha^{-1})				BEP (USD/USD per t)				Credit vulnerability			
	2011	2012	2013	Mean (± SEM)	2011	2012	2013	Mean (± SEM)	2011	2012	2013	Mean (± SEM)
'Cristalina'												
Non-irrigated	58.3	20.3	43.8	40.8 ± 11.1	4.5	7.6	6.0	6.0 ± 0.9	1.2	2.1	1.6	1.6 ± 0.3
Supplemental irrigation	134.0	41.8	58.3	78.0 ± 28.4	5.5	10.4	8.6	8.2 ± 1.4	1.4	2.4	2.1	2.0 ± 0.3
Full irrigation	118.6	36.5	76.4	77.2 ± 23.7	6.1	11.9	8.2	8.7 ± 1.7	1.4	2.4	1.6	1.8 ± 0.3
'Roja Lisa'												
Non-irrigated	70.8	52.7	56.0	59.8 ± 5.6	4.2	5.4	5.2	4.9 ± 0.4	1.0	1.2	1.2	1.1 ± 0.1
Supplemental irrigation	184.3	100.2	62.5	115.7 ± 36.0	5.0	6.7	8.3	6.7 ± 0.9	1.1	1.5	2.0	1.5 ± 0.3
Full irrigation	215.0	94.7	81.9	130.5 ± 42.4	5.1	7.6	8.0	6.9 ± 0.9	0.9	1.4	1.6	1.3 ± 0.2

cactus pear cultivars in the three growing seasons (Table 2). Supplemental irrigation can be considered as an economically feasible irrigation strategy for cactus pear farmers [19]. This achievement was possible because the inputs involved in supplemental irrigation were less costly than those used in full irrigation, combined with the high sale prices for fruit yield prevailing during the harvest season. The latter was also observed in sub-irrigated peaches cultivated under the subtropical conditions of Zacatecas, Mexico [21]. Other marketing aspects to be considered for this exotic fruit, regardless of high selling prices at the start of the harvest season, is its ethnobotanical value [7] and relative short season, which make it an attractive fruit alternative for consumers over other temperate commodities (table grapes, apples, pear, plum, and Mexican cherry). This last factor may explain, in part, the economic feasibility of non-irrigated cactus pear (Table 2).

The yields of peaches [25] and olives [26] significantly improved by application of supplemental irrigation. However, these research studies were not accompanied by an economic analysis. In this study, supplemental irrigation increased the fruit yield (similar to fully irrigated plants), its effect was reflected in slightly more than double the irrigation use efficiency, gross water productivity, and net water productivity of cactus pear cultivation (Table 3). This effect was attributed to fewer economic inputs (electricity, irrigation time, and manpower) used in supplemental irrigation. While improving the yield and quality of cactus pear fruit [27], this irrigation technique is a better tool for conserving water than either deficit irrigation or partial rootzone drying irrigation strategies for this xerophytic crop [14].

Improved fruit yields imply a great demand for labor [27]. Over three years, supplemental irrigation averaged either similar ('Cristalina') or even a little bit less ('Roja Lisa') labor productivity than full irrigation (Table 4). Therefore, supplemental irrigation of cactus pear not only enhances yield productivity and fruit quality [28], but also has a great socio-economic impact due to the increased labor productivity, compared to non-irrigated plants [21]. In consequence, the positive and the minimum values of the break-even-point suggested a profitable fruit yield for both cactus pear cultivars under all three irrigation strategies (Table 4). The latter issue is supported by the mean fruit yield (± standard error) generated by the treatments in 'Cristalina'. The three-year production averages were 12. 6 ± 1.7 t ha^{-1}, 16.7 ± 4.0 t ha^{-1}, and 16.9 ± 4.9 t ha^{-1} for non-irrigated, supplemental, and full irrigation, respectively. The corresponding values for 'Roja Lisa', in the same order, were: 4.6 ± 1.1 t ha^{-1}, 8.4 ± 3.1 t ha^{-1}, and 10.1 ± 3.3 t ha^{-1}, respectively [17]. Our break-even-point values are in good agreement with those generated for pineapple, another plant with crassulacean acid metabolism [29], under an organic production system [20].

Cactus pear cultivation in this production area (11,688 ha) is mainly under non-irrigated conditions (94.7%) [15]. However, the positive values for credit vulnerability derived from this study indicate that cactus pear farmers are good candidates for accessing agricultural credit [22]. The last finding may explain why some farmers combine both cactus pear production systems (irrigated and non-irrigated orchards) (Table 4).

5. CONCLUSION

After a three-year evaluation, our hypothesis was accepted. Despite the increased inputs with irrigation, the supplemental irrigation strategy produced the best agricultural economic indices at or above the level of the fully irrigated treatment with less input for both cactus pear cultivars. Additionally, supplemental irrigation should be recommended as a feasible irrigation strategy for both cultivars and similar agroecological systems, since it provided comparable fruit yield and used 52% less water than fully irrigated plants. It is also important to highlight that based on the positive values of credit vulnerability, the productivity of cactus pear orchards under full irrigation, supplemental irrigation, or without irrigation makes cactus pear growers meet the criteria for agricultural credit. However, agronomic and economic benefits of supplemental irrigation require further studies in other cactus pear genotypes rainfed grown, using both harvested water and groundwater.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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