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Mineral nutrition enhances yield and affects fruit quality of 'Cristalina' cactus pear

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ABSTRACT

Cactus pear (*Opuntia* spp.) responds positively to supplemental organic and mineral nutrition. There are several recommended rates and sources of mineral nutrition for this crop. However, there is no information on ways to produce optimal fruit yield in cactus pear. The objective of this study was to test a nitrogen–phosphorus–potassium (NPK) fertilization matrix over three consecutive growing seasons and to determine its effect on yield and fruit quality of 'Cristalina' cactus pear. In the second and third growing seasons, mineral nutrition significantly increased fruit yield. Average yields were 9.6, 12.1, and 21.6 t ha^{-1} for the 2004, 2005, and 2006 growing seasons, respectively. Supplemental nutrition at a rate of 90N–30P–30K increased fruit yield 13.4- and 5.2-fold in the 2005 and 2006 growing seasons, respectively, over unfertilized control plants. Application of K alone had no effect on fruit yield. Therefore, the maximum biological response of fruit yield was estimated at 30.3 t ha^{-1} with 90 kg ha^{-1} N and 30 kg ha^{-1} P. Although fruit number increased, fruit size, as mean fruit weight, was similar among treatments. Fruit quality, determined as peel firmness, peel to pulp ratio, and total soluble solids concentration, exhibited inconsistent responses to supplemental mineral nutrition. Fruit dry matter was reduced as N and P application rates increased. Cladode macro- and micronutrients were found in sufficient concentrations, except for Mn. Even when Mn was at high concentrations, no toxic effects were observed in cactus pear plants. Spearman rank correlation between some fruit quality attributes and nutrient concentrations found a significant positive association between fruit firmness and cladode K concentration, but negatively association between TSSC and cladode N and K concentrations. Nutrient use efficiency decreased as N and P application rates increased. After plant and soil mineral analysis, the 90 kg ha^{-1} N and 30 kg ha^{-1} P could be applied to production sites by cactus pear growers. The lack of fruit yield response from cactus pear to K fertilization should be studied further because cactus pear extracts ~54 kg K $year^{-1}$. Over the long term, this constitutes an important drain on the ecosystem if no K is added back.

1. Introduction

Opuntia spp. is cultivated extensively in ~57,000 ha of semi-arid and arid highlands in central and north-central Mexico. This plant is also being introduced in similar production areas worldwide for alleviating soil erosion, animal feed, human consumption as vegetable (young cladodes) or fruit, and industrial purposes (Mondragón-Jacobo, 2001; Nefzaoui and Ben Salem, 2002; Guevara et al., 2009; Iturriaga et al., 2009; Pichler et al., 2012). This succulent plant exhibits crassulacean acid metabolism (CAM), a photosynthetic mechanism to withstand limited availability of water or CO_2 (Cushman and Bohnert, 1999). Thus, such plants are more efficient in producing dry matter per unit water consumed than C_3 and C_4 plants (Taiz and Zeiger, 2006). For instance, cactus pear (*Opuntia ficus-indica*) cultivated for fruit can produce higher yields (5.7 t ha^{-1}) than beans (0.4 t ha^{-1}) and maize (1.0 t ha^{-1}) under rainfed conditions in the north-central highlands of Mexico (SIAP, 2012). A more detailed study comparing productivity of C_3, C_4, and CAM plants has been published (Nobel, 1994).

Productivity of cactus pear exploited for fruit production is variable worldwide (Nerd et al., 1991; García de Cortázar and Nobel, 1992; Inglese, 1995; Claassens and Wessels, 1997; Pimienta-Barrios and Ramírez-Hernández, 1999; Galizzi et al., 2004; Zegbe and Mena-Covarrubias, 2009; Luna-Vázquez et al., 2012). In part, fruit yield variation is due to the availability of germplasm (Mondragón-Jacobo, 2001), orchard design, and management (Inglese, 1995; Fernández-Montes and Mondragón-Jacobo, 1998). Cactus pear productivity was increased significantly with irrigation (Barbera, 1984; Nerd et al., 1989) and particularly with supplemental organic or mineral nutrition (Pimienta-Barrios

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and Ramírez-Hernández, 1999). Many mineral nutrition studies have examined off-season fruit production (Nerd et al., 1991, 1993; Nerd and Mizrahi, 1994; Zegbe and Mena-Covarrubias, 2008). For regular cropping, various nitrogen, phosphorus, and potassium (NPK) fertilization regimens have been studied. These differed in fertilizer source, amount, and application timing; not surprisingly, these studies have produced inconsistent results (Pimienta-Barrios, 1986; Gathaara et al., 1989; Nerd and Mizrahi, 1994; Inglese, 1995; Inglese et al., 1999; Fernández-Montes and Mondragón-Jacobo, 1998; Sáenz-Quintero, 1998; Ochoa and Uhart, 2006; García-Herrera et al., 2008; Felker and Bunch, 2009) or showed no effect on yield (Karim et al., 1998; Galizzi et al., 2004). Other researchers explored various NPK rates, but these reports did not optimize the biological yield response of cactus pear to NPK soil application (Gathaara et al., 1989; Claassens and Wessels, 1997; Pimienta-Barrios and Ramírez-Hernández, 1999; Galizzi et al., 2004; Ochoa and Uhart, 2006). Cladode tissue concentrations of NP were more useful than soil concentrations to optimize fruit yield of non-cultivated cactus pear (*Opuntia engelmannii*) (Gathaara et al., 1989). The effect of mineral nutrition on cactus pear fruit quality, measured as fruit size, fresh weight, pulp weight, pulp to peel ratio, peel firmness, and total soluble solids concentration, has received little attention and results have been inconsistent (Karim et al., 1998; Galizzi et al., 2004). The objective of this study was to test a NPK fertilization matrix on yield and fruit quality of 'Cristalina' cactus pear over three consecutive growing seasons. As with other fruit crops such as peaches (Zegbe-Domínguez and Rumayor-Rodríguez, 1996), it was expected that a positive biological response would allow yield to be optimized. The 'Cristalina' variety was selected because it is widely cultivated for its fruit in Mexico.

2. Materials and methods

2.1. Experimental site

The experiment was conducted in a commercial orchard at the Rancho la Tunera in Jerez, Zacatecas, Mexico (lat. 22°32′N, long. 103°03′W, elevation 1976 m) during three consecutive growing seasons from 2004 to 2006. The experimental site has an annual mean temperature of 25.7 °C and receives 482 mm precipitation with 62% occurring between July and October. Average annual pan evaporation is 2245 mm. The orchard soil is classified as Fluvisol with a sandy-loam to loam texture, pH between 6.1 and 7.4, organic matter from 1% to 1.56%, and cation exchange capacity (in meq $100\,g^{-1}$ soil) from 13.8 to 26.5. Soil fertility analysis, before the fertilizers were applied, indicated a total concentration ($mg\,kg^{-1}$) of 0.71 inorganic $N–NO_3$, 10 total N, 2.0 to 3.2 P, 520 to 1173 K, 1834 to 4440 Ca, and 213 to 234 Mg. The base change relationships were moderate (4.9) to high (7.7) for Ca/Mg, and very low for Mg/K (0.58–0.73), Ca + Mg/K (4.3–5.0), and Ca/K (4.0).

2.2. Plant material and orchard management

Four-year old cactus pear plants (*Opuntia albicarpa* Scheinvar var. 'Cristalina') were used. 'Cristalina' is a late-maturing, white-pulped type. Plants were spaced at 4 m × 3 m and trained to an open vase system. Weeds between plant rows were mowed and weed infestation around plants was controlled mechanically with hand pulling and digging. Except for fertilization, plants received standard cultural practices used for local commercial production including cladode pruning, row irrigation, and pest control as needed. Every season, fruit crop load was manually adjusted by thinning every second flower bud along the cladodes (Zegbe and Mena-Covarrubias, 2010). When flower buds appeared in pairs, the stronger flower bud was kept and the weaker one removed.

Table 1
Mineral nutrition treatments applied to 'Cristalina' cactus pear plants for three consecutive growing seasons from 2004 to 2006 in Jerez, Zacatecas, Mexico.

Treatment	Mineral nutrient application rates ($kg\,ha^{-1}$)		
	Nitrogen	Phosphorus	Potassium
1	0	0	0
2	0	30	30
3	30	30	30
4	60	30	30
5	90	30	30
6	60	45	30
7	60	60	30
8	60	30	0
9	60	30	60
10	90	60	60

Depending on the season, irrigation was applied over four or five events during the dry season (April–June). Two to three weeks after harvest (September or October), depending on the soil moisture and the presence of rain, an additional irrigation was given every growing season to make a second N fertilization as explained below. Cactus pear plants received 300, 317, and 320 mm in 2004, 2005, and 2006, respectively. These amounts of water considered irrigation and precipitation, where the effective rainfall (ER) (event rainfall ≥5 mm for local weather conditions and cactus pear) was estimated from accumulated rainfall (AR) in mm with the equation: $ER = (AR-5) \times 0.8$ (Zegbe and Serna-Pérez, 2012).

2.3. Mineral nutrient treatments and experimental design

The mineral nutrition supplements were nitrogen (N), phosphorous (P), and potassium (K). Rates were: 0, 30, 60, and 90 $kg\,N\,ha^{-1}$; 0, 30, 45, and 60 $kg\,P\,ha^{-1}$, and 0, 30, and 60 $kg\,K\,ha^{-1}$. Along with the nitrogen treatments, 34.3, 68.6, 102.8 kg of sulfate ha^{-1} were applied, respectively. Treatments were arranged in an incomplete factorial matrix (Table 1). The field trial was conducted in a randomized complete block design with three replications. There were ten experimental units per block that were randomly allocated to ten mineral nutrition treatments. Each experimental unit consisted of five consecutive plants in a row. At least three unfertilized plants at each end surrounded the experimental plots.

2.4. Fertilization program

For each fertilization treatment, half of the N and all of the P and K were applied with irrigation at the start of bloom on 6 April 2004, 19 April 2005, and 21 April 2006. The remaining half of the N was applied two to three weeks after fruit harvest with or without irrigation, depending on the residual soil moisture. This was done on 19 October 2004 and 2005, and on 22 September 2006. The sources for N, P, and K were ammonium sulfate, triple phosphate, and potassium chloride, respectively.

2.5. Data collection

2.5.1. Fruit yield

Fruit was collected from the two central plants of each plot at export harvest maturity skin color (yellowish-green). Harvest was done over six events in 2004 and seven in 2005 and 2006. Harvests started on 30 August 2004, 24 August 2005, and 18 July 2006. Fruit from each plant was harvested, graded by equatorial diameter into four categories (4.1 to 4.9, 5.0 to 5.9, 6.0 to 7.0, and >7.0 cm), and counted. The total weight of all fruit on a plant was measured as gross yield. Mean fresh weight of fruit was calculated by dividing the gross yield by the number of fruits per tree.

2.5.2. Fruit quality

To assess fruit quality at harvest, nine fruits per treatment (three per replication) were picked randomly at the fourth harvest from the outer perimeter of the plants. This was done on 5 October 2004, 13 September 2005, and 22 August 2006. Fruit quality measures were: peel firmness, total soluble solids concentration (TSSC), peel and pulp weights, and dry matter concentration (DMC). After removing the fruit skin, two flesh firmness determinations were done on two opposite sides of each fruit's equator using a press-mounted penetrometer (model FT 327, Wagner Instruments, Greenwich, CT, USA) with an 11.1-mm head. The TSSC of the juice from each fruit was measured using a digital refractometer with automatic temperature compensation (model PR-32α, Atago, Ltd., Tokyo, Japan). The peel and pulp were separated and weighed to determine the pulp-to-peel ratio. The DMC was determined from 25 g of a composite sample of fresh cortical tissue taken from three fruit, then oven-dried at 65 °C for a week.

2.5.3. Cladode sampling and nutrient analysis

Macro- and micronutrient concentrations were determined from a one-year-old, fruiting cladode of the central plant from each plot. Samples were collected from the apical side of the cladode. The tissue samples were obtained with a coring device. Samples were collected on 21, 12, and 7 July of 2004, 2005, and 2006, respectively. Each sample was washed with distilled water, dried at 65 °C for 36 h to constant weight, and ground. Cladode tissues were wet-digested using a micro Kjeldahl apparatus to determine N concentration. For determination of other nutrients, samples were also wet-digested and analyzed with an inductively coupled plasma emission spectrometer (Fisons Instruments, Dearborn, MI).

2.5.4. Nutrient use efficiency

Nutrient use efficiency was estimated as agronomic efficiency (AE), expressed as the additional economic yield per nutrient applied (Fageria et al., 1997; Baligar et al., 2001):

$$\mathrm{AE} = \frac{[\text{Yield F (kg)} - \text{Yield C (kg)}]}{\text{Amount of nutrient applied (kg)}} = \quad \text{kg} \quad \text{kg}^{-1}$$

where F and C are plants receiving fertilizer and no fertilizer, respectively.

2.6. Data analysis

The data were analyzed as a complete randomized block model using the GLM procedure. The effects of N and P on yield were studied individually by orthogonal contrasts keeping fixed two out of the three nutrients and by response surface analysis using the REG and RSREG procedure of SAS software (Version 9.1; SAS Institute, Cary, NC, USA), respectively. The orthogonal contrasts (C_n) for N were: C_1: t_1 (00N–00P–00K) versus t_2 (00N–30P–30K), t_3 (30N–30P–30K), t_4 (60N–30P–30K), t_5 (90N–30P–30K); C_2: t_2 versus t_3, t_4, t_5; C_3: t_3 versus t_4, t_5; C_4: t_4 versus t_5. For P were: C_1: t_1 (00N–00P–00K) versus t_4 (60N–30P–30K), t_6 (60N–45P–30K), t_7 (60N–60P–30K); C_2: t_4 versus t_6, t_7; C_3: t_6 versus t_7. The main effect of K was tested by *t*-test between t_4 (60N–30P–30K) and t_9 (60N–30P–60K). The percentage of fruit weight per fruit category was arcsine transformed and means are reported after back transforming. Treatment means were separated by the Tukey's test at $p \leq 0.05$. Mean nutrient concentrations are presented followed by 95% confidence intervals.

3. Results and discussion

3.1. Fruit yield

Unlike in previous reports (Gathaara et al., 1989; Karim et al., 1998; Galizzi et al., 2004), the cactus pear 'Cristalina' responded positively to added soil mineral nutrition. Average fruit yield ± twice SE was: 9.6 ± 1.0, 12.1 ± 1.8, and 21.6 ± 2.6 t ha^{-1} for the growing seasons of 2004, 2005, and 2006, respectively. Ochoa et al. (2002) found that the effect of soil fertilization was observed the following year, particularly when high nitrogen applications were used (200 to 300 kg ha^{-1}). The last finding was partially confirmed in this experiment because fruit yield was statistically ($p \leq 0.05$) the same among fertilizer treatments in the first (2004) growing season. However, rather than high nitrogen rates, a fertilizer rate of 90N–30P–30K kg ha^{-1} increased fruit yield 13.4-, 5.2-, and 3.6-fold in the 2005 and 2006 growing seasons and on a 3-year average, respectively, over the yield of unfertilized plants. The other treatments had responses intermediate between the 00N–00P–00K and 90N–30P–30K treatments (Table 2). The lack of cactus pear response to mineral nutrition in the first growing season suggests that these plants require a cumulative stimulus. This fruit yield pattern has been observed in peaches growing in a low fertility soil (Zegbe-Domínguez and Rumayor-Rodríguez, 1996). As with other fruit trees (Neilsen et al., 2010), soil water availability via irrigation, rainfall, or both is crucial for nutrient acquisition from soil in cactus pear (Claassens and Wessels, 1997). This experiment was conducted under both irrigation and rainfall; this could contribute to mineral uptake by the roots and was reflected in fruit yield.

An interesting response among treatments 1 (00N–00P–00K), 2 (00N–30P–30K), and 3 (30N–30P–30K) was also observed (Table 2). In the first two treatments, yield was reduced in 2005 compared to 2004 and 2006. This could be due to alternate bearing in cactus pear plants receiving no N, mainly (Pimienta-Barrios and Ramírez-Hernández, 1999). The positive effect of N can be seen in treatment 3 (and in the rest of treatments containing N), where yield increased consistently during the three consecutive growing seasons.

The design of this experiment allowed the individual influences of N, P, and K to be examined. This was done using the 2006 dataset. For N the orthogonal contrasts (C_n) detected significant and non significant differences in C_1 (F = 13.73; p = 0.001), C_2 (F = 15.14; p = 0.001), and C_3 (F = 4.31; p = 0.053), and C_4 (F = 0.64; p = 0.433), respectively. For P C_n detected significant and non significant differences in C_1 (F = 9.04; p = 0.01) and C_2 (F = 9.56; p = 0.01), and C_3 (F = 1.95; p = 0.181), respectively. Supplying N and P to the soil positively explained fruit yield variability, in terms of coefficient of determination (r^2), by 76% and 58%, respectively, which had not been demonstrated previously (Gathaara et al., 1989; Inglese, 1995; Fernández-Montes and Mondragón-Jacobo, 1998; Sáenz-Quintero, 1998; Inglese et al., 1999; Pimienta-Barrios and Ramírez-Hernández, 1999; García-Herrera et al., 2008) (Fig. 1A and B). However, the highest mean response of fruit yield (26.9 to 30.6 t ha^{-1}) was observed between 60 and 90 kg N ha^{-1} until the third growing season (Fig. 1A). These last results do not support previous findings (Gathaara et al., 1989; Claassens and Wessels, 1997; Ochoa and Uhart, 2006). Claassens and Wessels (1997) set the maximum yield (4.0 t ha^{-1}) at 60 kg N ha^{-1} until the fourth evaluation cycle; while Ochoa and Uhart (2006) reached ≈13.5 t ha^{-1} by applying 100 to 150 kg N ha^{-1} until the second growing season. These differences may be due to different soil type and fertility, different varieties with different genetic crop loads, plant age, and irrigation and rainfall availability. The maximum mean response of fruit mass (26.9 to 20.9 t ha^{-1}) for this study was between 30 and 60 kg P ha^{-1} until the third growing season (Fig. 1B). Claassens and Wessels (1997) did not set a maximum fruit yield by applying

Table 2
Effect of various mineral nutrition treatments on yield of 'Cristalina' cactus pear in Jerez, Zacatecas, Mexico. The mean values (±twice SE) in the last column are a three-year average. Mean separations within a column were by Tukey's test at $p < 0.05$.

Treatment	Mineral nutrition rates (kg ha^{-1})			Fruit yield (t ha^{-1})			
	N	P	K	2004	2005	2006	Mean
1	0	0	0	08.3a	01.6d	05.8c	05.7 ± 2.6
2	0	30	30	07.9a	02.4d	11.6bc	07.3 ± 2.6
3	30	30	30	08.8a	13.0bc	20.6abc	14.1 ± 3.2
4	60	30	30	09.7a	12.2bc	26.9ab	16.3 ± 4.6
5	90	30	30	09.6a	21.4a	30.6a	20.5 ± 4.8
6	60	45	30	09.3a	12.2bc	21.9abc	14.7 ± 4.0
7	60	60	30	08.3a	09.2cd	19.9abc	12.5 ± 3.6
8	60	30	0	13.6a	14.0bc	24.5ab	17.3 ± 3.6
9	60	30	60	10.0a	13.3bc	21.9abc	15.1 ± 3.8
10	90	60	60	10.3a	18.1ab	26.9abc	18.4 ± 4.0
Significance				0.737	0.0001	0.005	
Minimum significant difference				10.1	6.5	16.7	

P to the soil, perhaps because the P range explored was relatively narrow.

In this study, K application did not affect fruit yield ($F = 1.01$; $p = 0.994$). Rather than soil fertilization, cladode K concentration partially explains cactus pear yield, but at high (>3%) cladode K concentrations, the fruit number per cladode may be reduced (Karim et al., 1998). In this experiment, both soil K (from 520 mg kg^{-1} to 1173 mg kg^{-1}) and K added to the soil could have overridden their effect on fruit yield; in fact, cladode K and K soil concentration were similar to that offered by Galizzi et al. (2004). The K tissue values (mean ± 95% confidence interval) were: 3.2 ± 0.2% and 3.86 ± 0.28% for this experiment and Galizzi et al. (2004), respectively. The K soil concentrations were 520 mg kg^{-1} to 1173 mg kg^{-1} for this experiment and 1160 ± 53 mg kg^{-1} for Galizzi et al. (2004). *Opunita* species can grow on a wide range of K soil concentrations: from one report of 95 mg kg^{-1} to 257 mg kg^{-1} (Nobel, 1983), to those reported by Galizzi et al. (2004) and here.

Despite our finding that application of K did not affect fruit yield, it is important to consider that cactus fruit is 2% dry weight K, so assuming a fruit yield of 27 t ha^{-1} and a dry weight of 10%, these cacti extract 54 kg K from the soil each year. This creates an unsustainable, long-term, drain on the ecosystem if no K is applied. Therefore, this issue deserves further study.

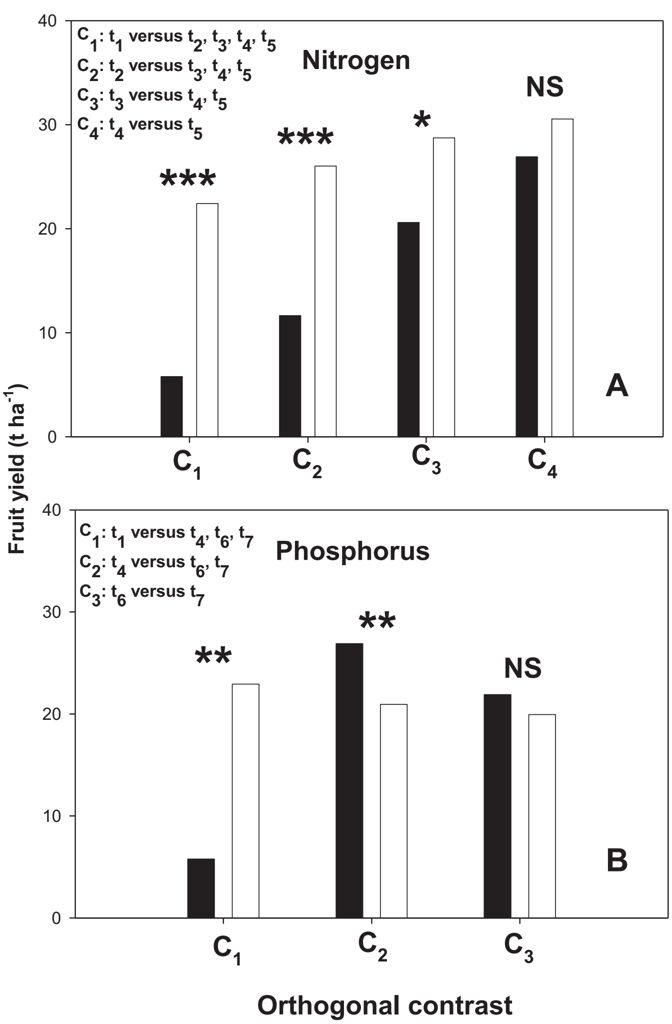

Fig. 1. Influence of nitrogen (A) and phosphorus (B) application on fruit yield of 'Cristalina' cactus pear in Jerez, Zacatecas, Mexico. The asterisks *, **, ***, or NS indicate statistical differences by orthogonal contrasts at $p \leq 0.05$, $p \leq 0.01$, $p \leq 0.001$, or non significant, respectively.

3.2. *Maximum fruit yield*

Based on the N and P responses described previously, we calculated the fertilizer regimen that maximized fruit yield. The response surface analysis showed that the fitted model explained 45% of fruit yield variability in terms of linear, quadratic, and cross-product effects of N and P. The lack of fit test did not reject the null hypothesis ($F = 0.43$; $p = 0.651$) and indicated a maximum value as stationary point (Mannan et al., 2007). The fitted response surface model was: Fruit yield $= 6.13 + 0.19\text{N} - 1.93 \times 10^{-4}\text{N}^2 + 0.41\text{P} - 7.1 \times 10^{-3}\text{P}^2 + 1.1 \times 10^{-3}\text{NP}$. This model estimated ≈30.3 t ha^{-1} as the maximized fruit yield by using 90 kg ha^{-1} N and 30 kg ha^{-1} P. Such information had been not reported previously for a cultivated cactus pear variety (Gathaara et al., 1989; Nerd et al., 1989; Nerd et al., 1991; Nerd and Mizrahi, 1994; Inglese, 1995; Claassens and Wessels, 1997; Fernández-Montes and Mondragón-Jacobo, 1998; Karim et al., 1998; Sáenz-Quintero, 1998; Inglese et al., 1999; Pimienta-Barrios and Ramírez-Hernández, 1999; Galizzi et al., 2004; Ochoa and Uhart, 2006; García-Herrera et al., 2008; Felker and Bunch, 2009).

3.3. *Fruit size*

As with fruit yield, the number of fruits was similar among treatments in the first year of evaluation, but mean fruit weight was higher in treatment 7 (60N–60P–30K) than in the other treatments ($p \leq 0.05$). The higher mean fruit weight in treatment 7 could be due to lesser sink-organs, in terms of fruit number. However, the relationship between mean fruit weight and fruit number was only 9.6% (r^2; $p = 0.016$). This is consistent, in part, with previous findings for other fruit trees (Wünsche et al., 2000; Crisosto et al., 1997) and for

Table 3
Effect of various mineral nutrition treatments on fruit number (FN) per plant and mean fruit weight (MFW) of 'Cristalina' cactus pear in Jerez, Zacatecas, Mexico. Mean separations within a column were by Tukey's test at $p < 0.05$.

Treatment	Mineral nutrient rates (kg ha^{-1})			Years of evaluation					
				2004		2005		2006	
	N	P	K	FN	MFW (g)	FN	MFW (g)	FN	MFW (g)
1	0	0	0	68a	156.1ab	11d	169.2a	38b	183.7a
2	0	30	30	63a	152.4b	18d	160.0a	85ab	168.3a
3	30	30	30	58a	173.7ab	106bc	153.0a	149ab	168.9a
4	60	30	30	65a	180.3ab	92bc	161.3a	190a	172.8a
5	90	30	30	60a	191.8a	177a	148.1a	226a	164.8a
6	60	45	30	63a	184.8ab	94bc	154.3a	170ab	159.8a
7	60	60	30	52a	194.5a	70cd	157.9a	150ab	164.2a
8	60	30	0	91a	172.9ab	97bc	173.9a	179ab	168.7a
9	60	30	60	66a	183.5ab	103bc	156.8a	175ab	153.8a
10	90	60	60	67a	188.0ab	137ab	159.1a	190a	172.4a
Significance				0.7	0.01	0.0001	0.61	0.02	0.75
Minimum significant difference				8	38.9	63	40.4	143	46.8

cactus pear (Zegbe and Mena-Covarrubias, 2009, 2010). In 2005 and 2006, the control (00N–00P–00K) and treatment 5 (90N–30P–30K) had the fewest and most fruits, respectively. Fruit size was similar among mineral nutrition treatments in the second and third growing seasons (Table 3). This indicates an inverse relationship between fruit number and fruit size which could result from an intense inter-fruit competition for assimilates. In this experiment, over a three-year average, fruit size decreased linearly as fruit number increased, but this relationship explained only 10.9% (r^2; $p = 0.01$) of fruit size variability. This relationship was also observed in 'Amarilla sin Espinas' (Ochoa and Uhart, 2006) and 'Rojo Liso' (Zegbe and Mena-Covarrubias, 2009) cactus pear and in other fruit crops (Crisosto et al., 1997; Marini, 2003).

3.4. Fruit size distribution

Only fruit in the first three quality categories (Categories 1, 2, and 3), which include the most marketable fruit, were include in this report (Table 4). The number of category 1 fruit (>7.0 cm fruit diameter, extra fruit) was similar among treatments, at <2 kg per plant during the three growing seasons. In 2005 and 2006, treatments 5 (90N–30P–30K) and 10 (90N–60P–60K) consistently produced the highest fruit yield in categories 2 (first class fruit) and 3 (second class fruit); meanwhile, the lowest fruit yield was in the control. The first class fruit yields were subjected to a response surface analysis. The maximum value was estimated ≈9.0 kg plant^{-1} by using 90 and 30 kg ha^{-1} N and P, respectively. To our best knowledge, there is no available information regarding cactus pear fruit grading in plants receiving supplemental mineral nutrition. However, this fruit sorting pattern was similar to that reported for peach trees given supplemental mineral nutrition during three consecutive growing seasons (Zegbe-Domínguez and Rumayor-Rodríguez, 1996).

3.5. Fruit quality

As in temperate fruit crops (Neilsen et al., 2010; Fallahi et al., 2010), mineral nutrition plays a central role on fruit quality regardless of yield, particularly N (Kingston, 1991; Crisosto and Mitchell, 2002). Yield and fruit size increased with N application rates (Crisosto et al., 1997), but fruit firmness decreased (Westwood, 1993). However, here mean peel firmness at harvest in 2004 was not altered by supplemental mineral nutrition. In 2005, the peel was firmer in treatments without N (1, 00N–00P–00K, and 2, 00N–30P–30K) than in those with N. In the third growing season, treatments 5 (90N–30P–30K) and 7 (60N–60P–30K) produced the least and most firm peel, respectively (Table 5). Galizzi et al. (2004) found a non-significant tendency toward greater fruit firmness in treatments with P, K, and N. Our data did not confirm this when the main effects of N, P, and K were analyzed. Fruit firmness was similar at all N, P, and K application rates in 2004 and 2006, but in 2005, it decreased as N and P applications increased. The firmness (Newtons) values (minimum significance difference (MSD) = 22.6; $p = 0.01$) were 62.2, 45.5, 37.0, and 34.8 at 0, 30, 60, and 90 kg N ha^{-1}, respectively. The firmness values (MSD = 24.7; $p = 0.06$) were 62.0, 41.0, 35.6, and 38.3 for 0, 30, 45, and 60 kg P ha^{-1}. The association between fruit size and fruit firmness by growing season did not explain these two fruit dimensions. The significance values were $p = 0.05$, $p = 0.2$, and $p = 0.6$ for the 2004, 2005, and 2006 growing seasons, respectively. However, the correlation between fruit firmness and pulp weight could explain the relationship between these two variables only in 2005 ($r^2 = 20.2\%$; $p = 0.0001$). The corresponding values for 2004 were $r^2 = 0.25\%$ and $p = 0.637$ and for 2006 were $r^2 = 2.9\%$ and $p = 0.102$. We used color peel break as a harvest index, but evidently there are additional factors controlling firmness in cactus pear fruit to be studied and understood.

The pulp to peel ratio was not affected by supplemental mineral nutrition in 2004 and 2006. In 2005, treatments 1 (00N–00P–00K) and 2 (00N–30P–30K) had the lowest peel to pulp ratio and treatment 5 (90N–30P–30K) the highest. This was because the edible part of the fruit was proportionally greater in the treatments supplemented with NPK, consistent with Galizzi et al. (2004). However, the main effects of N, P, and K indicated that only N and P increased pulp weight. The values were 0.8, 1.0, 1.2, and 1.3 for 0, 30, 60, and 90 kg N ha^{-1} (MSD = 0.3; $p = 0.01$). The values were 0.9, 1.1, 1.2, and 1.2 for 0, 30, 45, and 60 kg P ha^{-1} (MSD = 0.29; $p = 0.04$). This finding was relevant only in 2005; therefore, both firmness and pulp to peel ratio require further study to clarify fully the effects of supplemental nutrition.

Total soluble solids concentration (TSSC), like the other quality attributes, showed an inconsistent response to supplemental mineral nutrition. In 2004, treatment 5 (90N–30P–30K) had the lowest mean TSSC, while the remaining treatments were statistically similar. In contrast, treatments 2 (00N–30P–30K) and 3 (30N–30P–30K), and treatments 1 (00N–00P–00K) and 2 (00N–30P–30K) had the highest mean TSSC in the 2005 and 2006 growing seasons, respectively. The lowest mean TSSC values were found in treatment 7 (60N–60P–30K) in 2005 and 2006 (Table 5). N soil applications could not be responsible, because the main effect of N indicted similar TSSC values among N application rates over the three growing seasons. The significance values were $p = 0.05$, $p = 0.08$, and $p = 0.3$ in 2004, 2005, and 2006, respectively. The same was true for the main effect of P and K in 2004 and 2005, but in 2006, both P and K reduced TSSC as their application rates increased.

Table 4
Effect of various mineral nutrition treatments on fruit size distribution of 'Cristalina' cactus pear in Jerez, Zacatecas, Mexico. Mean separations within a column were by Tukey's test at $p < 0.05$.

Treatment	Mineral nutrient rates (kg ha^{-1})			Fruit size distribution (kg per plant in each diameter category)								
				1 (>7 cm)			2 (7.0–6.0 cm)			3 (5.9–4.0 cm)		
	N	P	K	2004	2005	2006	2004	2005	2006	2004	2005	2006
1	0	0	0	0.0a	0.1a	0.6a	3.1b	1.0c	4.7c	5.9a	0.8c	1.6b
2	0	30	30	0.1a	0.0a	0.1a	3.2b	1.4bc	7.3bc	5.1a	1.5cd	6.3ab
3	30	30	30	0.7a	0.2a	0.2a	6.7ab	5.6abc	14.8ab	3.1a	8.7abc	8.9ab
4	60	30	30	0.9a	0.3a	0.8a	6.8ab	7.1a	14.6ab	3.5a	6.9bcd	16.3ab
5	90	30	30	1.6a	0.0a	0.7a	7.1ab	9.0a	17.2a	2.5a	15.3a	18.0a
6	60	45	30	0.1a	0.7a	0.4a	7.1ab	6.9a	11.5abc	3.8a	6.1bcd	12.8ab
7	60	60	30	1.2a	0.4a	0.6a	6.2ab	5.1abc	12.7abc	2.4a	5.2bcd	9.8ab
8	60	30	0	0.7a	0.7a	0.5a	8.5a	8.5a	12.2abc	6.5a	7.3bcd	16.1ab
9	60	30	60	0.7a	0.1a	0.5a	7.6ab	7.3a	9.6abc	3.5a	7.9bcd	13.8ab
10	90	60	60	0.9a	0.7a	0.7a	8.6a	9.5a	18.8a	2.8a	11.0ab	12.3ab
Significance				0.7	0.7	0.6	0.005	0.0001	0.002	0.07	0.0001	0.02
Minimum significant difference				2.0	5.7	1.4	5.0	5.7	9.4	4.6	7.6	15.3

The values were 12.5, 11.8, 11.1, and 10.4 Brix for 0, 30, 45, and 60 kg P ha^{-1} (MSD = 1.4; $p = 0.006$). The values were 12.4, 11.3, and 11.5 Brix for 0, 30, and 60 kg K ha^{-1} (MSD = 0.9; $p = 0.03$). These unconvincing results led us to explore the possibility of a dilution effect due to fruit size, but the negative correlation between fruit size and TSSC did not explain the effect either. The significance was $p = 0.2$, $p = 0.8$, and $p = 0.7$ in the 2004, 2005, and 2006 growing seasons. Compared to other quality attributes, and as part of the fruit dry matter concentration, we were expecting more consistent results for TSSC. Exploring the relationship of cladode mineral concentration with TSSC might better explain the lack of NPK soil application influence not only for TSSC, but also for firmness and pulp to peel ratio. However, studies in this field have showed mixed results. Karim et al. (1998) found that fertilized wild cactus pear plants had higher TSSC than unfertilized plants, while Galizzi et al. (2004) found no relationship between 11 cladode nutrients and TSSC.

Fruit dry matter concentration (FDMC) was similar among treatments in 2004. In contrast, treatments 5 (90N–30P–30K) and 10 (90N–60P–60K), the highest N application rates, had lower mean FDMC than fruits from unfertilized control plants in 2005. This result held only for treatment 5 in 2006. On the other hand, pulp weight was higher in treatments supplemented with nitrogen than in unfertilized treatments (data not shown). The FDMC also correlated negatively with pulp weight ($r = -0.37$; $p = 0.0003$). The reduced FDMC in treatments 5 and 10 suggests that unfertilized fruit could have smaller, more densely packed cells than fertilized fruit.

3.6. Macro- and micronutrient concentrations

The analysis of variance detected no significant effect of supplemental mineral nutrition on individual macro- and micronutrient concentrations in the three years evaluated (data not shown). As with other fruit crops (Westwood, 1993), cladode Ca and Mg concentrations increased during the reproductive growing season, while cladode N and K were high early in the reproductive season, but their concentrations fell 30 days after blooming, and remained relatively stable for the rest of the season (Gugliuzza et al., 2002). Our cladode samples were collected during the later growing stage, which could explain the lack of significant differences among treatments. Nevertheless, pooled analysis of three years' data revealed that mean cladode P, K, Ca, Fe, and N, Mg, and Zn concentrations were similar and relatively lower, respectively, than those reported by Galizzi et al. (2004). In contrast, cladode Mn, Cu, and B, particularly Mn, were higher (Table 6) than reported values (Galizzi et al., 2004; Nobel, 1983). Tissue concentrations of Cu and B were in the normal range for most crops, but not Mn (Bennett, 1993). The later author indicates that >300 mg kg^{-1} and >500 mg kg^{-1} (Jones, 1972) could be toxic for most crops. Here we found a low positive relationship between cladode Mn concentration and fruit yield ($r^2 = 23.1\%$; $p = 0.0001$), but a marginally significant ($p = 0.05$) and negative relationship ($r^2 = 4.1\%$) between cladode K concentration and fruit yield, and non significant ($p = 0.89$) relationship between cladode N concentration and fruit yield which may disagree with those results offered by Karim et al. (1998). However, cladode samples were taken on July when N and K concentration were the

Table 5
Effect of various mineral nutrition treatments (T) on some 'Cristalina' cactus pear fruit quality attributes at harvest in Jerez, Zacatecas, Mexico. Mean separations within a column were by Tukey's minimum significant difference (MSD) at $p < 0.05$.

T	Mineral nutrition rates (kg ha^{-1})			Peel firmness (N)			Pulp to peel ratio			Total soluble solids (%)			Dry matter (mg g^{-1} fresh weight)		
	N	P	K	2004	2005	2006	2004	2005	2006	2004	2005	2006	2004	2005	2006
1	0	0	0	59.5a	62.9a	57.5ab	1.0a	0.9c	1.0a	11.1a	11.9ab	12.5a	188.1a	205.7a	199.9a
2	0	30	30	59.2a	62.4a	56.5ab	1.0a	0.8c	1.1a	11.2a	12.5a	12.2a	181.5a	201.1ab	186.8ab
3	30	30	30	67.6a	45.5ab	53.7ab	1.0a	1.0bc	1.1a	10.2a	12.6a	11.1ab	183.1a	198.5ab	186.4ab
4	60	30	30	69.6a	34.3b	39.2bc	1.0a	1.0bc	1.2a	10.6a	11.5ab	12.2a	181.5a	188.7ab	190.5ab
5	90	30	30	67.3a	37.0b	32.4c	1.0a	1.3a	1.3a	8.3b	11.4ab	11.5a	178.0a	171.5 b	167.8b
6	60	45	30	63.5a	35.6b	42.7abc	0.9a	1.2ab	1.1a	9.9a	11.5ab	11.1ab	193.2a	188.1ab	170.5b
7	60	60	30	74.0a	43.7b	66.2a	1.0a	1.1ab	1.0a	10.0a	10.3b	9.5b	184.0a	183.0ab	177.2ab
8	60	30	0	74.5a	38.4b	39.6bc	0.9a	1.2ab	1.3a	10.6a	11.0ab	12.2a	187.5a	180.7ab	184.3ab
9	60	30	60	67.9a	32.7b	37.8bc	1.1a	1.2ab	1.2a	11.0a	12.0ab	11.8a	180.2a	175.6ab	173.6ab
10	90	60	60	67.9a	32.8b	49.6abc	1.0a	1.3a	1.2a	11.2a	12.0ab	11.2a	178.2a	171.1 b	180.0ab
Significance				0.6	0.0001	0.0001	0.6	0.0001	0.2	0.0001	0.001	0.0001	0.9	0.01	0.01
MSD				27.7	17.7	23.9	0.3	0.2	0.4	1.5	1.7	1.6	36.a	34.0	28.2

Table 6
Influence of N, P, and K soil application treatments (T) on cladode macro- and micronutrient concentrations of 'Cristalina' cactus pear in Jerez, Zacatecas, Mexico. Mean values are followed by 95% confidence intervals.

T	N	P	K	Macronutrients (%)					Micronutrients (mg kg^{-1})				
	(kg ha^{-1})			N	P	K	Ca	Mg	Fe	Zn	Mn	Cu	B
1	0	0	0	0.62 ± 0.1	0.14 ± 0.02	3.1 ± 0.3	5.8 ± 0.8	0.94 ± 0.1	44.3 ± 09.9	17.7 ± 3.7	528.2 ± 263.4	15.3 ± 08.6	75.9 ± 34.2
2	0	30	30	0.58 ± 0.1	0.23 ± 0.07	3.1 ± 0.6	6.0 ± 0.6	0.89 ± 0.1	42.2 ± 19.0	17.3 ± 3.3	667.6 ± 267.5	23.8 ± 16.5	73.9 ± 25.4
3	30	30	30	0.69 ± 0.1	0.25 ± 0.04	3.6 ± 0.7	5.2 ± 0.5	0.90 ± 0.1	42.0 ± 10.6	20.2 ± 3.7	862.7 ± 347.6	18.5 ± 11.9	63.2 ± 14.0
4	60	30	30	0.72 ± 0.1	0.26 ± 0.04	3.0 ± 0.8	5.8 ± 1.2	0.94 ± 0.2	45.6 ± 13.5	19.1 ± 3.7	855.1 ± 185.4	16.7 ± 11.5	66.0 ± 17.8
5	90	30	30	0.81 ± 0.1	0.22 ± 0.05	3.2 ± 0.6	5.9 ± 1.0	0.92 ± 0.1	46.4 ± 13.0	17.8 ± 3.5	718.7 ± 345.5	21.7 ± 12.0	64.2 ± 24.7
6	60	45	30	0.75 ± 0.1	0.28 ± 0.06	3.2 ± 0.6	5.7 ± 1.2	0.85 ± 0.1	49.5 ± 12.5	19.7 ± 4.7	738.3 ± 302.9	19.2 ± 10.7	57.2 ± 18.7
7	60	60	30	0.69 ± 0.1	0.28 ± 0.07	3.0 ± 0.7	5.7 ± 1.4	0.92 ± 0.1	57.2 ± 37.1	21.0 ± 4.9	801.0 ± 281.2	22.5 ± 13.4	69.6 ± 06.9
8	60	30	0	0.73 ± 0.1	0.22 ± 0.03	3.3 ± 0.7	5.5 ± 0.7	0.97 ± 0.1	42.7 ± 12.9	19.6 ± 3.0	792.1 ± 229.7	15.2 ± 11.3	65.7 ± 20.5
9	60	30	60	0.82 ± 0.2	0.25 ± 0.05	3.3 ± 0.8	6.2 ± 0.9	0.90 ± 0.1	44.2 ± 12.0	18.2 ± 4.5	829.4 ± 405.8	22.2 ± 21.0	83.0 ± 23.1
10	90	60	60	0.81 ± 0.2	0.27 ± 0.05	3.3 ± 0.7	5.3 ± 1.1	0.87 ± 0.3	43.5 ± 01.5	18.1 ± 3.6	740.1 ± 232.4	17.1 ± 10.9	71.9 ± 22.6
Mean				0.72 ± 0.04	0.24 ± 0.01	3.2 ± 0.2	5.7 ± 0.3	0.91 ± 0.04	45.6 ± 4.4	18.9 ± 1.0	753.3 ± 78.4	19.2 ± 3.5	69.1 ± 6.2
Coefficient of variation (%)				24.4	30.4	26.1	22.3	21.2	45.5	26.2	49.6	86.3	43.0

lowest during the growing season (Gugliuzza et al., 2002), hence the lack of a positive relationship between them (at the whole plant level) and fruit yield as suggested by Karim et al. (1998).

Spearman's rank correlation (r_s) was used to examine the relationships between some fruit quality attributes and nutrient concentrations. The r_s value ranged from weak to moderate. Firmness was positively correlated with K (r_s = 0.43; p = 0.0001), Mg (r_s = 0.31; p = 0.003), and Zn (r_s = 0.42; p = 0.0001), but negatively correlated with Fe (r_s = −0.28; p = 0.008), Cu (r_s = −0.43; p = 0.0001), and B (r_s = −0.33; p = 0.001). Pulp weight weakly correlated with N (r_s = 0.28; p = 0.008); similarly, FDMC also weakly correlated with Mn (r_s = 0.25; p = 0.02). The TSSC correlated positively with Cu (r_s = 0.28; p = 0.007) and B (r_s = 0.31; p = 0.004), but negatively with N (r_s = −0.26; p = 0.01), K (r_s = −0.34; p = 0.001), and Zn (r_s = −0.31; p = 0.0001). Some correlations found here support previous results (e.g., firmness versus K) (Galizzi et al., 2004), but others were contradictory (e.g., TSCC versus N and K) or not correlated (e.g., TSCC versus Mg) (Karim et al., 1998; Galizzi et al., 2004). These discrepancies could be attributed to the cladode tissue sampling date and fruit phenological stage. Here, the former and later data were collected at the start of exponential fruit growth and at harvest, respectively. Therefore, further research on fruiting cladodes is required to understand nutrient movement from cladode to fruit at different fruit phenological stages.

3.7. Nutrient use efficiency

Nitrogen use efficiency (NUE) was the same among nitrogen application rates in 2004. In 2005, NUE was highest at 30 kg N ha^{-1}. This trend was similar (p = 0.2) in 2006. Phosphorus use efficiency (PUE) was similar among application rates in 2004, but consistently highest at 30 kg P ha^{-1} (Table 7). An inverse linear association between nutrient application rates and nutrient use efficiencies was observed. For instance, correlations between NUE and nitrogen rates were −0.3, −0.79, and −0.92 in 2004, 2005, and 2006, respectively. The corresponding PUE values, in the same order, were −0.93, −0.94, and −0.95. The NUE and PUE reduction suggests that these two nutrient use efficiencies are close to maximum for fruit production. Lower nutrient use efficiencies indicate a risk of nutrient loss to the environment that may contribute to its degradation (Fageria et al., 1997; Hedlund et al., 2003). Nevertheless, annual plant and soil nutrient diagnosis (Weinbaum et al., 1992; Baligar et al., 2001) and fertigation (Hartz, 1993; Hanson et al., 2006) could minimize possible harm to the environment, because these three agronomic practices are compatible with sustainable agriculture.

Table 7
Nutrient use efficiency of nitrogen and phosphorus in terms of agronomic use efficiency for 'Cristalina' cactus pear in Jerez, Zacatecas, Mexico. Mean separations within a column were by Tukey's test at p < 0.05.

Mineral nutrient rates (kg ha^{-1})	Agronomic use efficiencies (kg kg^{-1})		
	Years of evaluation		
	2004	2005	2006
Nitrogen use efficiency			
0	–	–	–
30	5.1a	74.6a	92.9a
60	7.1a	34.5b	54.8a
90	4.2a	40.2b	49.5a
Significance	0.9	0.03	0.2
Minimum significant difference	40.9	32.0	70.7
Coefficient of determination (%)	34	52	48
Phosphorus use efficiency			
0	–	–	–
30	28.1a	162.8a	240.6a
45	12.2a	103.2b	152.6ab
60	09.3a	088.8b	125.9b
Significance	0.3	0.001	0.01
Minimum significant difference	49.5	35.9	110.9
Coefficient of determination (%)	6	16	25

4. Conclusions

Supplemental mineral nutrition improved yield and fruit size of 'Cristalina' cactus pear in the second and third growing seasons. The maximum fruit yield was estimated at 30.3 t ha^{-1} using application rates of 90 and 30 kg ha^{-1} N and P, respectively. Potassium added to the soil did not contribute significantly to fruit yield. Although crop load was adjusted in all plants, mean fruit weight was reduced as fruit number increased. Fruit quality, in terms of peel firmness, peel to pulp ratio, and total soluble solids concentration, showed no clear responses to supplemental mineral nutrition, except for fruit dry matter concentration, which was higher in fruits from unfertilized plants than in fruits from plants supplemented with P + K or N + P + K. Nevertheless, fruit size distribution, particularly of first and second class fruit, was consistently enhanced by 90N–30P–30K and 90N–60P–60K. The optimum value for first class fruit was estimated at 9.0 kg plant^{-1} using 90 and 30 kg ha^{-1} N and P, respectively. Our soil was rich in K, but if no K is applied, cactus pear cultivation would create a significant drain on the ecosystem over time; further studies could quantify this requirement. Cladode nutrients were found in sufficient concentrations except for Mn, which was more abundant than previously reported, but no toxic effects were observed in cactus pear plants. Spearman's rank correlation between some fruit quality attributes and nutrient concentration found a positive association between fruit firmness and cladode K concentration, but a negative one between TSSC and cladode N and K concentration. Nitrogen and phosphorus use efficiency was greater at the lowest N and P application rates and vice versa. The lack of fruit yield response to K fertilization should be studied further, because of its relevance to cactus pear metabolism and the long-term ecological impact if no K is applied to the soil. Therefore, after plant and soil mineral analysis, an 90N and 30P kg ha^{-1} application rate is recommended to cactus pear growers to optimize production.

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