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Water Use Efficiency of Subsurface Drip Irrigation and Furrow Irrigation

지하점적관개와 고랑관개의 물 이용 효율

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Abstract

The primary objective of this study was to compare water use efficiencies between subsurface drip irrigation and furrow irrigation. The uniformity of used drip lines was tested to determine if clogging would be a threat to the long-term success of a subsurface drip irrigation system. Three crops, cantaloupe, lettuce, and bell pepper, were grown in four plots for each irrigation system. Significantly less water was applied with subsurface drip irrigation than with furrow irrigation (29.5 % less for cantaloupe and 43.2 % less for bell pepper) in order to produce similar crop yields. Water use efficiencies with subsurface drip irrigation were significantly higher than those with furrow irrigation for cantaloupe (P-value = 0.018) and bell pepper (P-value $\leq$ 0.001). Drip-irrigated lettuce, a shallow-rooted crop, had moderately higher water use efficiency during the first two seasons, while no difference was observed in the third season. After the experiment, the uniformity of the drip lines was 92.1 % on average and classified as good. The high values for water use efficiency and uniformity indicate that subsurface drip irrigation can be a sustainable method for conserving irrigation water.

Keywords : Subsurface drip irrigation, Furrow irrigation, Water use efficiency, Drip uniformity.

I. Introduction

To meet the newly increased demands for water due to population growth and agricultural and industrial development, additional water resources need to be developed (Arar, 1989). Such new developments, however, require a great deal of effort and may not be economically feasible. Therefore water conservation is of

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great importance, particularly in arid and semi-arid regions.

Considering that irrigation water use makes up a significant portion of fresh water use, the improvement of efficient water use in agriculture can contribute to the relief of water shortages. Lettuce is one of the most important winter crops in Arizona, supplying about 25% of the national demand in 2003. Arizona is also ranked second to California in cantaloupe production, averaging 5,624,000 hundredweight annually in 2003 (USDA-NASS, 2004).

Recent research results generally showed that crop yields with subsurface drip irrigation systems were equal to or better than other irrigation systems; in addition, subsurface drip irrigation used less water. Camp (1998) indicated that high-frequency subsurface drip irrigation produced higher tomato yields than low-frequency applications of the same amount of water. Bucks et al. (1981) showed that subsurface drip irrigation yields were comparable to those with furrow irrigation for cantaloupe, onion, and carrots. This study also reported an optimal average seasonal evapotranspiration of 51 cm for spring cantaloupe. Subsurface drip produced much higher cabbage yields than furrow irrigation in Arizona and had better water utilization because of reduced evaporation during the summer (Rubeiz et al., 1989). Hutmacher et al. (2001) reported 19 and 35 percent greater alfalfa yield with subsurface drip than furrow irrigation, while applied water rates for the two systems were similar. Fitz-Rodriguez (2002) and Suarez-Ray et al. (2000) reported equal or better turfgrass quality with subsurface drip irrigation as compared to sprinkler irrigation.

Oron et al. (1991) reported several advantages of subsurface drip irrigation, including reduced evaporation, greater weed control, and enhanced workability. Subsurface drip irrigation has been considered to be an effective technique to reduce crop contamination when wastewater is used for irrigation (Oron et al., 1991; Ruskin, 1992; Phene and Ruskin, 1995). Enriquez et al. (2003) reported that viral contamination of turfgrass was minimal using subsurface drip irrigation.

Camp (1998) reported a greater reduction in emitter uniformity for subsurface systems than for surface drip systems after eight years of use, primarily because of emitter plugging caused by soil entry into the main or sub-main during system modification. Emitter clogging by root intrusion was identified and the statistical uniformity of emitters was reduced from 91.8% to 86.2% without flow rate reduction after three years of turf irrigation (Choi and Suarez-Rey, 2004).

The primary purpose of this study was to compare subsurface drip irrigation with furrow irrigation in terms of produce yields and water use efficiency. In addition, after being used for two seasons of lettuce irrigation, the drip lines were tested for emitter uniformity.

II. Materials and methods

The three crops used in this study were cantaloupe (Mission variety hybrid, Willhite Inc., TX), lettuce (Beacon variety, Paragon Seed Inc., CA), and bell pepper (California Wonder, Willhite Seed Inc., TX). They were grown in the field at the Campus Agricultural Research Center of the University of Arizona, Tucson, AZ during the three growing seasons from 2001 and 2004.

1. Soil information

The soil in the experimental field was Gila fine sandy loam (coarse-loamy, mixed (calcareous), thermic Typic Torrifluvent). The texture of the soil was determined by Yousaf to be 53 % sand, 36 % silt, and 11 % clay (1995). Bulk density of the soil was 1.36 g/cm^3. The field capacity was 230 mm/m at a depth of 0 to 30 cm and saturated hydraulic conductivity was 2.15 cm/hr (Suttles, 1998). The permanent wilting point (PWP) determined by Copeland (1989) was 100 mm/m.

2. Field preparation

Eight plots (each 10 m (L)×8 m (W) for cantaloupe, 10 m (L)×5 m (W) for lettuce and bell pepper) were prepared in a field with an overall size of 50 m (L)×19 m (W) (Fig. 1). Four plots were subsurface drip irrigated and four were furrow irrigated. Pipe lines were installed to deliver irrigation water to each plot. The field was plowed and four seedbeds were established for each plot. The seedbeds were 110 cm wide – 20 cm tall for cantaloupe growth in 2003 and 55 cm wide – 20 cm tall for lettuce and bell

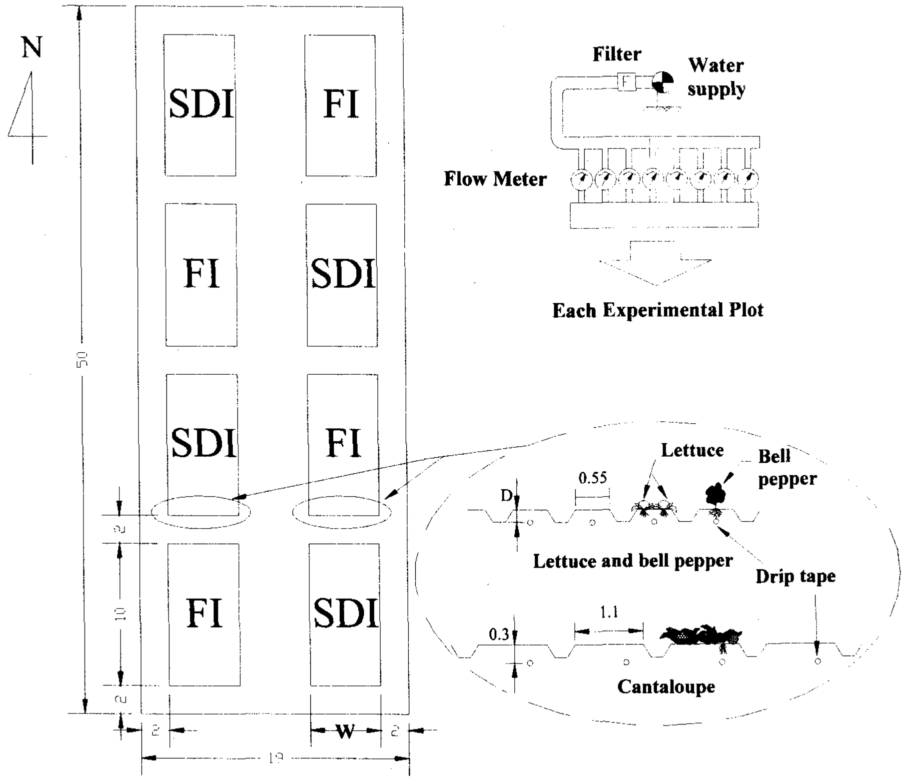

Fig. 1 Schematics of the experimental field (SDI and FI represent subsurface drip and furrow irrigation, respectively. Width (W) was 5 m for lettuce and bell pepper, and 8 m for cantaloupe. D indicates the drip line installation depth which was 0.15 m for lettuce, 0.20 m for bell pepper, and 0.30 m for cantaloupe. Unit: meter).

pepper in 2001 through 2003, and 2004, respectively. Furrows were leveled and both furrow ends in the furrow irrigation plots were blocked with soil to prevent tail water runoff. The Chapin ® turbulent twin-wall drip lines were buried at a depth of 30 cm for cantaloupe, 20 cm for bell pepper, and 15 cm for lettuce. Cantaloupe and bell pepper were seeded in a row whereas lettuce was seeded in two rows on each bed, following common commercial practices in Arizona.

The emitters were spaced 20 cm apart and design flow rate was 1.9 L/h per 30.5 meters of drip line at an operation pressure of 69 kPa. Sprinkler and subsurface drip irrigation were used to germinate seeds for cantaloupe and lettuce, respectively. Bell pepper was germinated on seedling beds and transplanted to the plots. Once the crops had been established in the field, the subsurface drip and furrow irrigation systems were separated.

3. Irrigation schedule

The climate of Tucson is characterized by a long, dry, and hot season from April to October (Table 1). Approximately 46% of Tucson's annual rainfall occurs during the summer monsoon season, normally lasting from early July through mid-September. Annual evapotranspiration amount is dominantly greater than annual rainfall and, therefore, irrigation is essential for Arizona crop production.

Irrigation was scheduled based on average soil moisture content. A time domain reflectrometer (TDR, Soilmoisture Equipment Corp., Minitrase, Santa Barbara, CA) was used to measure soil moisture content approximately every two days in three locations per plot. Wave guides of TDR were inserted vertically at a depth of 50 cm below soil surface for measurement.

Furrow irrigation events were scheduled when soil moisture levels approached the permanent wilting point (10 mm/m). The deficit of measured soil moisture to field capacity was applied during the following irrigation event. Irrigation water amounts were determined by multiplying the soil water deficit by the crop root zone depth. In the case of rain, irrigation stopped and resumed when soil moisture was depleted close to the wilting point. Most irrigation events took place during the late afternoon for about an hour so as to minimize evaporation water loss.

A total of 15 irrigation events occurred from 6/6 through 7/31 for cantaloupe; 18 events for bell pepper from 4/20 through 7/23, and 7 events for lettuce from 9/2 through 11/25. Cantaloupe was irrigated approximately twice a week with varying irrigation water depths of 30 to 50 mm

Table 1 Normal monthly rainfall and reference evapotranspiration in Tucson, Arizona (AZMET, 2005).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	SUM
Rainfall (mm)	26.6	25.5	21.7	10.8	4.7	6.2	44.9	44.7	24.1	20.6	16.6	28.6	275.0
*Reference ET (mm)	75.5	93.1	151.7	204.0	242.9	267.8	225.1	196.0	184.4	146.6	91.5	66.0	1944.6

* The Penman equation was used for reference Evapotranspiration (ET) estimates.

per event. Bell pepper irrigation was performed once a week at the beginning of the growing season (April to mid-June) and twice a week during summer (mid-June to July) with irrigation depth of 25 to 54 mm per event. Lettuce irrigation took place approximately once a week with irrigation water depths of 10 to 35 mm per event.

For subsurface drip irrigation during the 2001 and 2002 lettuce growths seasons, the same irrigation protocols were applied to subsurface irrigation as for furrow irrigation. Irrigation events occurred approximately once per week and resulted in a water depth similar to that of furrow irrigation. One of the advantages of pressurized irrigation systems, such as subsurface drip irrigation, is the ease of frequent irrigation. Intermittent irrigation was applied to subsurface drip irrigation plots in 2003 and 2004 to evaluate the water use efficiency of frequent irrigation. The irrigation intervals were determined such that the soil moisture content was maintained at close to field capacity. Schedules were implemented during the daytime (from 8 am to 6 pm): 20 minutes every hour for cantaloupe, 15 minutes every one-and-a-half hours for lettuce, and 30 minutes every two hours for bell pepper.

Irrigation stopped when it rained and resumed when soil moisture was depleted close to the wilting point.

4. Fertilization and pesticide application

Fertilizers were broadcast-applied before planting at the same rate for both irrigation systems. Total nitrogen applied as Urea-Ammonium-Nitrate (32%) was 30 kg/ha, 180 kg/ha, and 230 kg/ha for cantaloupe, bell pepper, and lettuce, respectively. The rate of 25 kg/ha of phosphorus was applied for cantaloupe, 125 kg/ha for bell pepper, and 300 kg/ha for lettuce. Pesticides were applied at the beginning of the growing season for cantaloupe and bell pepper, whereas pesticides and herbicides were applied during both seasons as needed for lettuce.

5. Harvest

Crops were randomly harvested in two 5 m, 3 m, and 1.5 m segments from the central rows of each plot for cantaloupe, lettuce, and bell pepper, respectively. This was because the other two rows were assigned to another crop sampling purpose (crop contamination investigations), although each plot held four rows. Fresh produce weights of harvested crops were measured immediately after collection and converted to produce yield per hectare.

6. Estimation of water use efficiency (WUE)

Overall agronomic water use efficiency was used to evaluate irrigation performance and estimated using the following equation (Hillel, 1998)

$$WUE = \frac{P}{W} \quad (kg/ha/mm)$$

where P and W represent crop production in kg/ha and the depth of water applied in mm, respectively.

Irrigation water and rainfall were included as water applied. Weather data from AZMET (2004), located within one kilometer east from the experimental plot, were used. The wind direction at the field was predominantly from the west during the day and from the east at night.

7. Uniformity test for drip lines

After two seasons of lettuce growth in the field, the drip lines from each subsurface drip irrigation plot were retrieved and tested for uniformity. Water pressurized at 69 kPa was supplied to one end of the retrieved drip lines while the other end was connected to a pressure gauge. Plastic cups placed under each emitter collected water for 15 minutes and the amounts of effluent were measured. Two new drip lines, 10 m long, were also tested to provide control samples. Uniformity was calculated statistically using the following equation (ASAE standard EP458, 1995)

$$Uniformity = \left(1 - \frac{q_d}{q_a}\right) \times 100 \ (\%)$$

where q_d and q_a are the standard deviation and the mean of emitter discharge rate, respectively.

A software package, MINITAB^{TM}(MINITAB Inc., Release 13.32, State College, PA), was used for statistical analysis.

Ⅲ. Results and discussion

The present study was initiated to evaluate water use efficiency for growing iceberg lettuce in 2001. Cantaloupe and bell pepper, two of the main crops produced in Arizona, were added to the investigation in 2003 and 2004, respectively. They have deeper root systems as compared to lettuce.

Growing seasons and climatic data are summarized in Table 2. The greatest rainfall, 86.6 mm, was recorded during the lettuce experiment in 2003. The average temperatures during experimental periods were typical averages for Tucson (AZMET, 2004). The lettuce experiment in 2002 was delayed by a month as compared to 2001 and 2003 due to hail damage.

The growing seasons for the study crops followed common farming practices in Arizona. Cantaloupe and bell pepper were harvested several times for approximately one month when

Table 2 Growing seasons and climatic data obtained from AZMET (Arizona meteorological network weather station)

Crops	Planting date	Harvest date	Rainfall (mm)	Air temperature (°C)			*RH (%)	Solar Radiation (MJ/m^2)
				Max	Min	Average		
Cantaloupe	3/26/03	7/1/03~ 7/31/03	49.0	42.7	2.1	25.9	25.0	26.5
Bell pepper	4/20/04	7/8/04~ 7/26/04	19.8	41.2	6.2	27.4	23.7	28.5
Lettuce	9/7/01	11/20/01	5.8	39.2	3.8	22.7	39.6	20.7
	10/2/02	12/13/02	31.2	34.1	2.3	15.6	45.4	16.4
	9/2/03	11/25/03	86.6	39.7	3.5	21.8	47.5	17.2

* Daily average relative humidity

** Hourly, daily, weekly, and monthly meteorological data sets are available on AZMET produce was mature enough for market, while lettuce harvesting was conducted on a single day. Such harvest practices are common for these crops in Arizona.

1. Applied water depth

The total depth of applied water included both irrigation water and rainfall. The water applied for germination was not considered as part of the total applied water amount.(Table 3). In general, cantaloupe and bell pepper required more water than lettuce. This is probably because both cantaloupe and bell pepper have longer growing seasons, including during summer, as compared to lettuce, which was grown in late autumn. Much less water was applied by subsurface drip irrigation than by furrow irrigation, with the exception of lettuce. The ratios of applied water by subsurface drip irrigation to the average amount applied by furrow irrigation are presented in Table 3. On average, only 70.5% and 56.8% of the water amounts used by furrow irrigation were required by the subsurface drip irrigation systems for cantaloupe and bell pepper, respectively. According to Camp (1998) and DeTar et al. (1996), 30 to 40% less water was required by subsurface drip irrigation systems to produce similar cotton yields.

However, no significant differences in applied water amounts were observed in the lettuce experiments. This might be because the dense root zone of lettuce is relatively shallow as compared to the other crops. Thus, applied water for lettuce was not as readily available for cantaloupe and bell pepper which had deeper root depths. A study conducted by Choi and Suarez-Rey (2004) indicated that water from the subsurface drip emitters did not reach close to the soil surface where the dense root zone of turf is located; thus, they reported no significant difference in the total amount of water applied

Table 3 Total amounts of water applied during growing seasons

Irrigation system	*Total applied water (mm)					***Ratio of applied water (SDI versus FI)				
	Cantaloupe	Bell pepper	**Lettuce			Cantaloupe	Bell pepper	**Lettuce		
	2003	2004	2001	2002	2003	2003	2004	2001	2002	2003
SDI1	422	429	208	184	262	67%	60%	100%	92%	103%
SDI2	450	369			260	71%	51%			103%
SDI3	446	396			253	71%	55%			100%
SDI4	464	441			254	73%	61%			100%
FI1	634	697	207	200	262	100%	100%	100%	100%	100%
FI2	633	725			247					
FI3	631	722			258					
FI4	630	730			250					

* Total applied water includes irrigation water and rainfall

** Average value for each system in 2001, 2002 (Each plot irrigation were measured only in 2003)

*** Ratio of subsurface drip irrigated (SDI) water amount to furrow irrigated (FI) water amount between subsurface drip and sprinkler irrigation.

2. Crop yields and water use efficiencies

Table 4 presents crop yields and water use efficiencies for the three crops. Lettuce showed the highest water use efficiency followed by cantaloupe and bell pepper. However, there were no significant differences in crop yields between the two irrigation systems for any crop, except for lettuce in 2001 (Fig. 2). Subsurface drip irrigation produced significantly greater lettuce yield in 2001 than furrow irrigation (P−value = 0.018). Lettuce yield in 2002 was lower as compared to 2001 and 2003 due to lower temperatures.

The average temperature during the lettuce experiment in 2002 was lower by approximately 7 ℃ than in 2001 and 2003 (Table 2). The lettuce used was a fall season variety rather than a winter variety, and the experiment in 2002 was delayed for approximately one month due to hail damage. The lettuce yield in 2003 with intermittent subsurface drip irrigation was significantly greater than in 2001 ($P=0.043$). However, this could be due to climatic or greater amount of water application, since the same trend was observed for furrow irrigation ($P=0.002$).

Water use efficiencies with subsurface drip irrigation were significantly higher than those with furrow irrigation for cantaloupe (P−value = 0.018) and bell pepper (P−value ≤ 0.001), as shown in Fig. 3. This is primarily because much less water was used with subsurface drip irrigation than with furrow irrigation for cantaloupe and bell pepper production, while the yields for both crops were similar. Only lettuce in 2001 showed significantly higher water use efficiency with subsurface drip as compared with furrow irrigation due to higher yields (P−value = 0.038). The water use efficiencies of lettuce in 2002 and 2003 were not significantly different between the two irrigation systems (P−value ≤ 0.245).

Table 4 Crop yields and water use efficiencies

Irrigation system and plot numbers	Production (ton/ha)					Crop water use efficiency (kg/ha/mm)**				
	Cantaloupe	Bell pepper	Lettuce			Cantaloupe	Bell pepper	Lettuce		
	2003	2004	2001	2002	2003	2003	2004	2001	2002	2003
*SDI1	117.1	55.0	61.5	51.5	68.6	277.7	128.2	295.4	279.1	262.4
SDI2	113.9	53.2	58.6	37.9	76.7	253.0	144.4	281.8	205.3	295.0
SDI3	86.0	52.5	61.2	44.8	60.9	192.7	132.6	294.4	242.8	240.4
SDI4	108.6	55.6	48.2	48.1	73.0	234.3	126.0	231.7	260.7	287.7
FI1	107.4	61.3	52.7	43.1	76.2	169.2	87.9	254.7	215.0	291.2
FI2	123.0	44.5	45.7	43.1	63.9	194.4	61.4	220.7	215.0	258.8
FI3	101.3	56.6	44.5	34.1	70.9	160.5	78.4	214.7	170.3	275.0
FI4	86.1	55.4	43.1	52.2	64.5	136.7	75.8	208.1	260.2	257.6

* SDI: Subsurface drip irrigation, FI: Furrow irrigation

** Crop production per ha with unit depth of irrigation water

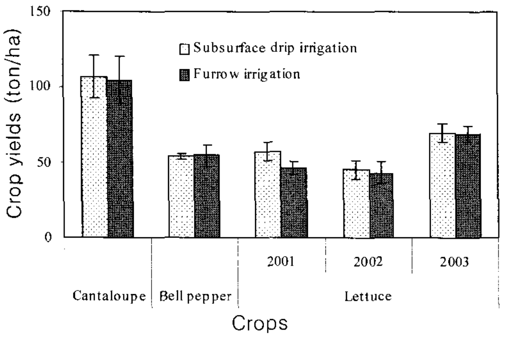

Fig. 2 Comparison of crop yields between irrigation systems (Error bars and the symbol* indicate standard deviations and statistical significance at the 95 % confidence level, respectively).

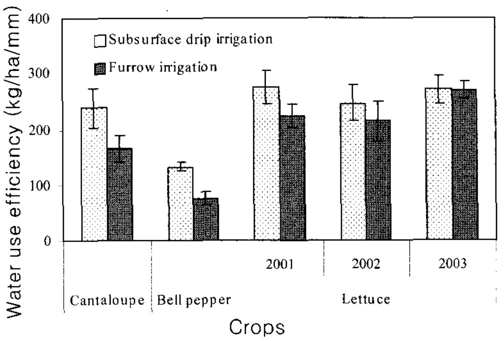

Fig. 3 Comparison of crop water use efficiencies between irrigation systems (Error bars and the symbol* indicate standard deviations and statistical significance at the 95 % confidence level, respectively).

3. Drip uniformity

Two unused and eight retrieved drip lines from the lettuce field were used for drip uniformity test; these drip lines had been buried underground for two years. The emitter flow rates of each drip line were measured. As summarized in Table 5, the average emitter flow rates from the retrieved drip lines were reduced by 5.9% on average, varying from 2.7% to 9.9%, as compared to unused drip lines. White precipitates were observed from some of the emitters. Thus, emitter clogging by ion precipitation appeared to cause flow rate reduction. However, no obvious root intrusion was observed. Uniformity of used drip lines was 92.1% on the average, varying from a low of 84.8% to a high of 96.9%. According

Table 5. Flow rates and uniformities of retrieved drip lines after two years of lettuce growth

*Samples	Flow rates of emitters (average±standard deviation, l/h)	Uniformity	**Number of impaired emitters out of 50 tested
Control 1	0.78 ± 0.02	97%	0
Control 2	0.77 ± 0.02	98%	0
SDI 1-1	0.74 ± 0.02	97%	0
SDI 1-2	0.74 ± 0.11	85%	1
SDI 2-1	0.72 ± 0.09	87%	1
SDI 2-2	0.73 ± 0.03	96%	0
SDI 3-1	0.70 ± 0.05	94%	3
SDI 3-2	0.71 ± 0.11	85%	3
SDI 4-1	0.75 ± 0.02	97%	1
SDI 4-2	0.75 ± 0.02	97%	1

* Control: new drip line, SDI: drip lines retrieved from subsurface drip irrigated plot

** No. of emitters of which flow rates are less than 90% of the average value to ASAE standard EP458 (1995) (95–100% as excellent, 85–90% as good, and 75–80% as fair), the uniformities tested were at least classified as good. Proper management of the water supply and chemical injections to prevent emitter performance degradation may have prolonged the longevity of these subsurface drip systems.

Ⅳ. Conclusions

Three crops, cantaloupe, lettuce, and bell pepper, were grown in the field using two irrigation systems, subsurface drip and furrow irrigation. Only 70.5% and 56.8% of the applied water for furrow irrigation was used for subsurface drip irrigation for cantaloupe and bell pepper, respectively. Lettuce required a similar amount of water. However, no significant differences in crop yields were observed between the irrigation systems except for lettuce in 2001.

Water use efficiencies with subsurface drip irrigation were significantly higher than with furrow irrigation for cantaloupe (P–value = 0.018) and bell pepper (P–value $\leq$ 0.001) due to much lower water requirements. Lettuce did not show a significant difference in water use efficiency except for in 2001 (P–value = 0.038).

The uniformities of used drip lines after two seasons of lettuce irrigation varied from 84.8% to 96.9% (92.1% on average) and were generally classified as good. It was concluded that subsurface drip irrigation can be an efficient technique in conserving water and may be more effective with crops with deeper root zone.

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