Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
http://dx.doi.org/10.5424/sjar/2014122-4756

Spanish Journal of Agricultural Research 2014 12(2): 519-526
ISSN: 1695-971-X
eISSN: 2171-9292

RESEARCH ARTICLE

OPEN ACCESS

Deep percolation in greenhouse-cultivated celery using the technique of subsurface film strips placement

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Abstract

To reduce the deep percolation during greenhouse vegetable cultivation, the technique of subsurface film strips placement was tested. Four treatments with two kinds of cross-sections (flat and U-shaped) and two different spacings (10 cm and 40 cm) of subsurface film strips were arranged in a greenhouse before planting celery. At the same time, a non-film treatment was arranged for comparison. Soil water content was measured and irrigation time was adjusted according to the soil water content. Evapotranspiration of celery during growth was calculated by the method of energy balance and the deep percolation was calculated by the equation of water balance. Deep percolation was reduced in all experimental treatments. Greater reduction in deep percolation was observed when using U-shaped cross-section strips compared with that using the flat cross-section strips. In addition, greater reduction in deep percolation was observed when the spacing between the film strips was smaller. The results of this test showed that the technique of subsurface film strips placement can reduce deep percolation and conserve irrigation water for greenhouse vegetables cultivation. However, the optimal layout variables for the use of the technique of subsurface film strips placement need further experimental and numerical analysis.

Additional key words: subsurface film strips placement (SFSP); *Apium graveolens;* deep percolation; water balance; energy-balance; water-saving irrigation; U-shaped strip placement; flat strip placement.

Introduction

The practice of placing a plastic film at certain depth below the ground surface to form an artificial impermeable layer to prevent the leakage of soil water and nutrients has been in use for decades. In the 1960s, researchers in the United States and Japan investigated the effects of placing an artificial impermeable layer of clay, plastic film or asphalt below the sandy layer (Cheng *et al*., 1986). A study by Chen & Qian (1984) showed that the placement of an impermeable plastic film beneath the shifting sands of the Tengger Desert in Ningxia, China, was helpful for increasing agriculture and forestry crop production. The practice of placing plastic film underneath deserts for the cultivation of agricultural and forestry crops eventually developed into the technique of film-bottomed sand land cultivation. The film of this technique covers all field horizontal projection plane below the root zone, *i.e.*, this technique uses the method of placing film underground to cover the entire extent of field. In recent years, this technique has been applied in rice cultivation and extended to large-scale settings in the Horqin desert in the eastern Inner Mongolia (Huang *et al*., 1994; Huang & Yan, 1995; Huang, 1995a,b; Zhao *et al*., 1995). A more in-depth study was conducted on applying this technique to wheat cultivation in deserts (Liu *et al*., 2000; Ling & Ren, 2004; Zhou *et al*., 2007). The method of placing film underground covering the entire extent of field has been also applied in conventional rice cultivation in paddy fields of non-desert areas.

The method of covering local extent of field when placing film underground has also been tested and applied in dry land. Barth (1999) proposed an impro-

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Received: 22-07-13. Accepted: 14-05-14.

Abbreviations used: DAP (diammonium phosphate); DP (deep percolation); E_t (crop evapotranspiration); I_w (water amount used for irrigation in the specified period); SFSP (subsurface film strips placement); SIS (improved subsurface irrigation system); WUE (water use efficiencies); ΔW (difference in soil water stored at the beginning and the end of the specified period).

ved subsurface irrigation system (SIS). Compared with conventional subsurface drip irrigation methods in dry land, SIS places V-shaped cross-section polyethylene film strips below each lateral pipe with emission points along it, leaving open spacing between the film strip rows. The film strips conserve the soil water from irrigation water and rainfall. Through the spacing area, excess water can seep into deeper soil layers during rainy periods. This is a typical method of subsurface local film placement in the field, which effectively reduces deep percolation and raises the movement of water towards the upper root zone, thereby improving irrigation efficacy. Wang *et al*. (2000) conducted a similar test in which the waterproof plastic film strips were placed below the subsurface drip tape. It was observed that the film strips significantly changed the distribution of water content of wetted soil around the drip tape (called wetted body). Compared with conventional subsurface drip irrigation, film strips increased the cross-section width of wetted body, improved the upward movement of the wetting front, reduced the downward infiltration depth of water, and increased the soil water content of the soil layer above the drip tape. Testing micro-emitters for subsurface irrigation in sandy land, Yu *et al*. (2007) placed a piece of square film below each emitter and observed that the film could improve the effect of irrigation. Previous studies show that the method of subsurface local film placement is more suitable for cultivation in dry land, and it can effectively reduce deep percolation and improve irrigation efficacy. Obviously, subsurface film strips placement (hereafter SFSP) is the easiest method of subsurface local film placement to apply. However, studies on SFSP and other subsurface local film placement are limited.

The root system of vegetables is generally shallow. The water requirement is big and the irrigation frequency is high for almost all vegetables. Thus, the traditional flood irrigation for vegetables often causes substantial deep percolation of soil water and nutrients (Yu, 2007; Fan *et al*., 2010). Greenhouse vegetables account for a considerably big proportion of the total vegetable supply in China. The main method of irrigation applied in a large proportion of these greenhouses is flood irrigation, and deep percolation is the major loss of the irrigation water. To solve this problem, a main strategy proposed is the adoption of sprinklers, drip or subsurface irrigation, other piping methods (Zhang *et al*., 2002; Chen *et al*., 2005; Cao *et al*., 2011) and the methods on basis of plastic film mulching on the ground surface, such as that the water flows above the film and seep into the soil through the holes of film, and irrigation under film (Shi & Meng, 2010; Zheng *et al*., 2010; Huang *et al*., 2012). However, the experimental studies on the method of subsurface local film placement used as main water-saving measure in vegetables cultivation are limited. This study is to improve the technique of SFSP, and to provide necessary references for its application through field vegetable planting test. The objectives of this study are: 1) to confirm the application feasibility and water-saving effects of SFSP in the greenhouse under flood irrigation, 2) to analyse the influence of SFSP on the movement processes of soil water, 3) to determine the reasonable layout variables of SFSP.

Material and methods

Study site

The study site is located in the Yingchengzi District of Dalian in Liaoning Province (China). It is at the southern end of the Liaodong Peninsula and on the east of Yellow Sea. It has a warm, semi-humid to humid continental monsoon climate with four distinctive seasons, mild weather with concentrated precipitation and monsoon winds. The study site is at a low altitude coastal plateau with an elevation of 15-30 m and groundwater depth of 10-15 m. The soil is thick and homogeneous. The soil texture of the field is medium or heavy loam, with little gravel and grit in the soil except the topsoil. The physical characteristics of the soil in the study site are shown in Table 1.

Table 1. Physical characteristics of the soil in the study site

Soil layer	Depth (cm)	Field capacity ($cm^3\ cm^{-3}$)	Permanent wilting point ($cm^3\ cm^{-3}$)	Dry bulk density ($g\ cm^{-3}$)	Saturated bulk density ($cm^3\ cm^{-3}$)	Saturated hydraulic conductivity ($cm\ s^{-1}$)
Topsoil	0-30	0.22	0.026	1.25	0.52	6.60×10^{-4}
Subsoil	>30	0.29	0.026	1.43	0.46	2.43×10^{-4}

Table 2. Layout variables of subsurface film strips of various treatments

Experimental treatments	Cross-section of strips	Layout variables (cm)				Horizontal projection of the strip (%)
		Horizontal projection width of strips	Spacing width between adjacent strips	Embedded depth of strips	Heigth folded up on both sides	
T1	None	—	—	—	—	—
T2	Flat	40	40	40	—	50
T3	Flat	40	10	40	—	80
T4	U-shaped	40	40	40	20	50
T5	U-shaped	40	10	40	20	80

A solar plastic greenhouse was used in the test, with insulation brick walls on the northern face and the sides (to the east and west). The ceiling of the greenhouse is made from lightweight steel pipe. The greenhouse occupies an area of 688 m^2, with an internal net width of 6.8 m, net height of 3 m and net length of 80 m. Excluding the area occupied by the water ponds and walkways, the size of the main area for celery cultivation was 6.2 m wide × 76.6 m long.

Experimental method

Four test treatments with two kinds of cross-section (flat and U-shaped) and two different film-strip spacings (10 cm and 40 cm) were arranged in this study as listed in Table 2. A non-film treatment was also arranged as a control treatment for comparison. The film used in this study was polyvinyl chloride membrane of 0.12-mm in thickness. The embedded depth of film strips for all tested treatments of SFSP was 40 cm below the ground surface. The width of horizontal projection plane of all film strips for all tested treatments of SFSP was 40 cm. The height folded up on both sides of cross-section with a 90 degree angle was 20 cm for all U-shaped strips used in this study. The cross-section view of SFSP along the length direction of strips is shown in Fig. 1.

The main planting area was divided into five zones to arrange five tested treatments (Table 2), with adjacent zones vertically separated by 1-m deep plastic films. The width of each zone in four SFSP treatments was 12 m. The ditching, laying film strips and backfilling of SFSP depended completely on manual work, with precaution to prevent mixing of the topsoil and subsoil. After the strips were placed, the backfill was irrigated so that it became fully subsided and compacted. Then, the five zones were levelled and ridged to form beds of a size of 1.5 m wide × 6.2 m long to plant celery.

The experiments were conducted between April and July 2009. The celery was planted on April 19 and harvested on July 1, with a total growth period of 73 day. The cultivar tested was the American Ventura celery (*Apium graveolens* var. 'Dulce Ventura'). Celery was planted in the bed with a density of 12 crops m^{-2}. Sowing and growing seedlings was carried out in another greenhouse before starting experiments. The crops were transplanted to the greenhouse when 7-8 leaves had sprouted. Approximately 7.5 kg m^{-2} of organic fertilizer and 75 g m^{-2} of diammonium phosphate (DAP) were applied as the base fertilizer.

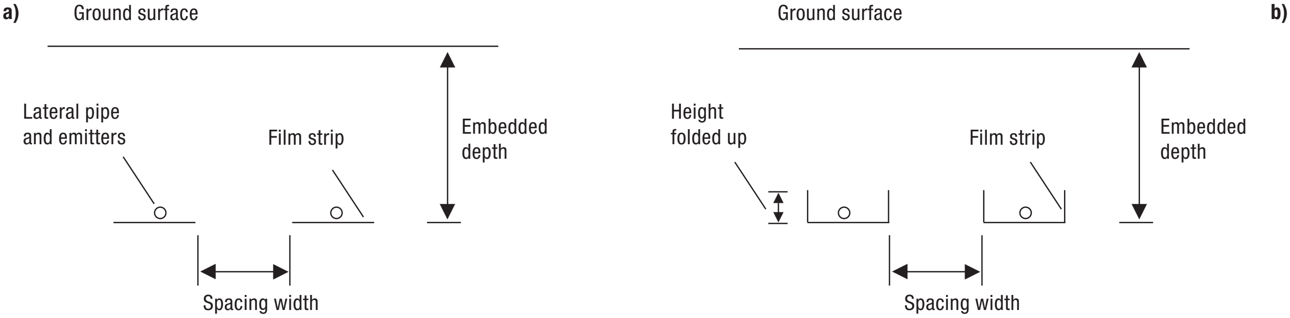

Figure 1. The sketch of subsurface film strips placement (SFSP): a) flat film strips, b) U-shaped film strips placement.

Meteorological data and soil water content in the greenhouse were measured continuously during the whole growing period from transplanting to harvesting. The minimum irrigation level was set at 65% of the field capacity of the root layer. Irrigation timing was determined according to the average soil content in the root zone. Flood irrigation with 40 mm of water per irrigation event was carried out, the same amount as local practices. The root layer of celery was set at a depth of 20 cm during the growing period of outer leaves from the transplanting. This depth was set at 30 cm during the period of stem sprouting and inner blades growing. Except for the irrigation timing, field management was the same for the five treatments.

Tests and data acquisition

An automatic weather station was set up in the middle of the main planting area to collect climatic data throughout the crop growth period. The collected data included net radiation, soil heat flux, wind speed, atmospheric pressure, relative humidity and temperature at heights of 50 and 200 cm. The FNP-1 net radiometer, installed at an elevation of 1.5 m from the ground, was utilized for net radiation measurements. Soil heat flux was measured by an HTH-2 soil heat flux meter which was 2-3 cm below the ground surface. Wind speed inside the greenhouse was generally slow, thus STF10V3 wind speed sensors were used which can measure wind speeds below 1 m s^{-1}. Temperature and humidity were measured by a DB4200SY11 temperature and humidity transmitter. Atmospheric pressure was measured by a LT/DY atmospheric pressure sensor. Output signals of all instruments in the automatic station are 4-20 mA or 0-5 V. The RSG30 data recorder (Ecograph T, E+H Company, Germany) was used for the continuous acquisition of measurement data with the sampling period of 15-min intervals.

The oven drying method was used to measure soil water content of 0-100 cm in the five treatments. When the average soil water content of root zone was close to the minimum irrigation level, the irrigation date was determined; the soil water content was measured two times, 1 day before irrigation and 1 day after irrigation. When the celery was transplanted and harvested, the soil water content of all zones was also measured.

The sampling points were placed both at the middle points of cross-section of film strips and at the middle points of spacing areas between adjacent film strips, and points were distributed both uniformly and randomly throughout each zone in each treatment, with at least six sampling points both on strips and on the spacing areas. At each sampling point, a soil auger was used to extract soil samples of 5 cm (height) × 4 cm (diameter) layer-by-layer down to a depth of 100 cm. An appropriate amount (weight) of soil was collected from the centre of each soil sample and placed in an aluminium box to measure water content. Each sampling location was clearly marked to ensure to avoid repeating sampling near this location in the future. After sampling, the drill-holes were backfilled and compacted with soil of the same texture as the corresponding strata.

Data analysis

The water balance equation was used to calculate the deep percolation of each experimental treatment. The amount of water retained within the body of the crops was excluded by taking into account the properties of vegetable growth. The deep percolation (DP) in this study is the accumulative amount that soil water flows through the bottom of 0-40 cm soil layer during the process that the soil water moves to the deeper layer. The relationship among DP, water amount used for irrigation in the specified period (I_w), difference in soil water stored at the beginning and the end of the specified period (ΔW) and crop evapotranspiration (E_t) is:

$$DP = I_w - \Delta W - E_t \qquad [1]$$

where all parameters were measured in mm.

E_t is calculated using the energy balance method with climatic data obtained within the greenhouse (Lei *et al*., 1988):

$$E_t = [(R_n - G)/(1 + \gamma(T_2 - T_1)/(e_2 - e_1))]/L \qquad [2]$$

where L is the latent heat of vaporization, MJ kg^{-1}; R_n is the net radiation, W m^{-2}; G is the soil heat flux, W m^{-2}; $\gamma = 0.665 \times 10^{-3}P$, a hygrometer constant, kPa °C^{-1}, being P the atmospheric pressure, kPa; T_1 and T_2 are the temperatures at the two heights, °C; and e_1 and e_2 are the vapour pressures at the two heights. Considering that environment conditions above each planting zones in the greenhouse were almost the same, we used the same E_t to calculate the deep percolation for each treatment. Based on the climatic data within the greenhouse, Fig. 2 shows the daily E_t, and the E_t for the entire growing period was 160.8 mm.

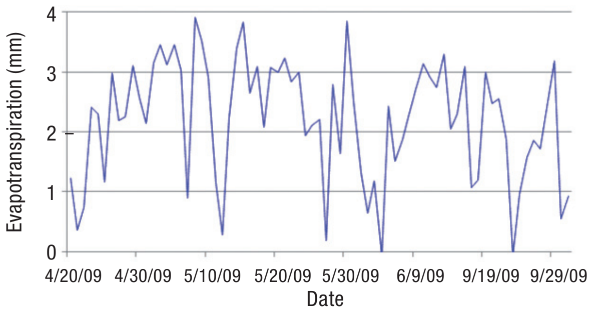

Figure 2. Daily celery evapotranspiration in the greenhouse (2009).

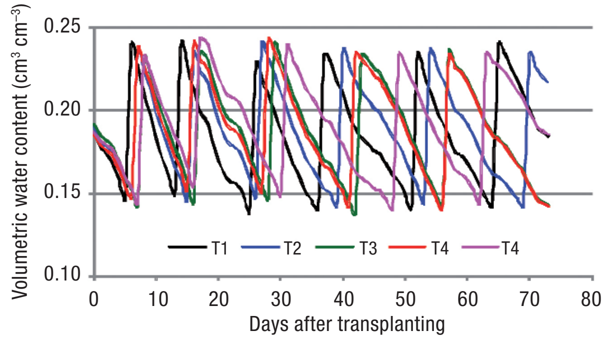

Figure 3. Average water content of 0-40 cm soil layer.

Results and discussions

The celery yields of all treatments were almost the same as the yield that local farmers can get. The yields and water use efficiencies (WUE) for all treatments are shown in Table 3. Yield differences were no significant among treatments. Compared with T1 (non-film treatment), the WUE of T3, T4 & T5 increased by about 20%. The WUE of T1 & T2 were almost the same. This shows that the SFSP technique is effective for greenhouse vegetables, and could achieve notable water saving under appropriate conditions. The effectiveness of SFSP was also proved by the evolution of average soil water content at the depth of 0-40 cm (Fig. 3). The average soil water content of 0-40 cm depth for various treatments of SFSP was similar to that of non-film treatment (T1). The soil water content of celery root zone can be controlled within an appropriate range during the whole celery growing period. The SFSP did not lead to excessive wetness in the root zone.

Table 3 also shows that the results of deep percolation for all treatments. The deep percolation was 80.2 mm for the non-film treatment (T1), *i.e.* about one-third of the total volume of irrigation water. This indicates that a substantial amount of irrigation water was lost through deep percolation, and it is necessary to take appropriate measures to reduce the deep percolation. The deep percolation of four SFSP treatments is in the range of 39.6-68.4 mm. Compared with T1, the deep percolation of the SFSP treatments was decreased by 14.7-56.0%, and it suggested that SFSP is an effective measure reducing the deep percolation.

Treatments T3, T4 & T5 had 40 mm less irrigation water than T1. Another influence on the irrigation of these SFSP treatments was that the time interval between adjacent irrigation events was increased by 1-3 days compared with non-film treatment (T1).

For the two treatments with flat film strips (T3 and T2), T3 had 40 mm (16.7%) and 9.8 mm (14.3%), less irrigation water and deep percolation than T2. For the two treatments of U-shaped film strips (T5 and T4), T5 had 16.7 mm (29.7%) less deep percolation than T4. This shows that under the condition of the same cross-section of film strips, the smaller the spacing width between adjacent film strips is, the better efficacy on water-saving and reducing deep percolation is.

For the two treatments with the same spacing width of 40 cm (T4 & T2), the irrigation water and deep percolation of T4 were lower than those values of T2 by 40 mm (16.7%) and 12.1 mm (17.7%), respectively.

Table 3. Results of water balance, yields and water use efficiencies (WUE) for all treatments

Experimental treatments	I_w (mm)	ΔW (mm)	DP (mm)	Yield (kg ha^{-1})	Percentage of yield difference to mean (%)	WUE (kg m^{-3})
T1	240.0	–1.0	80.2	71,774	–0.70	29.91
T2	240.0	10.7	68.4	72,177	–0.14	30.07
T3	200.0	–19.4	58.6	72,446	0.23	36.22
T4	200.0	–17.1	56.3	72,984	0.98	36.49
T5	200.0	–0.4	39.6	72,006	–0.37	36.00

I_w: water used for irrigation. ΔW: differences in soil water stored at the beginning and at the end of the treatment. DP: deep percolation.

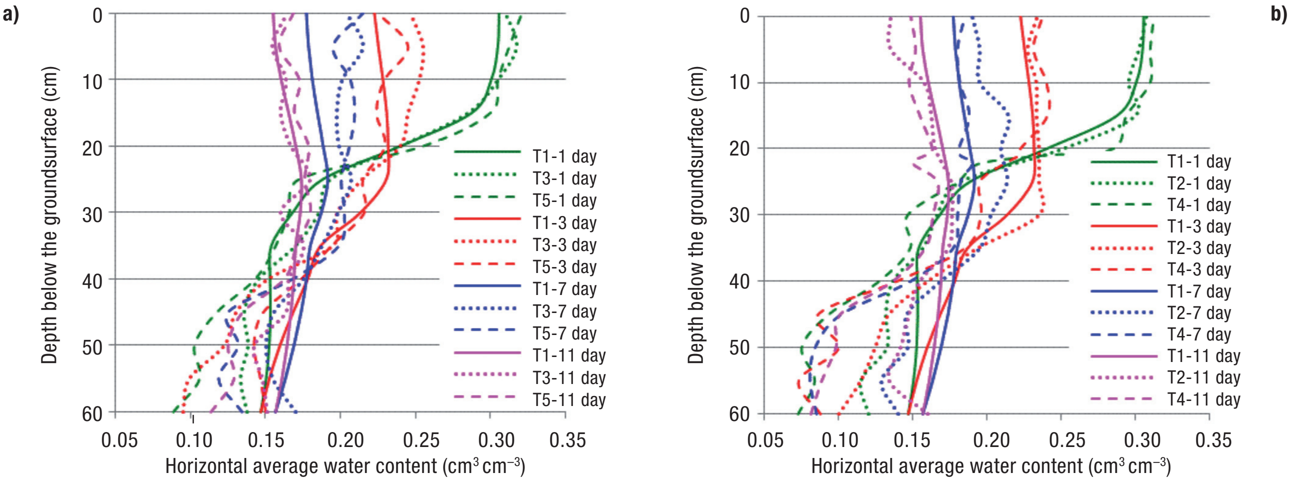

Figure 4. Distributions of horizontal average water content after fourth irrigation: a) comparison of treatments T1, T3 & T5, b) comparison of treatments T1, T2 & T4.

For the two treatments with the same spacing width of 10 cm (T5 & T3), the deep percolation of T5 was less than that of T3 by 19 mm (32.4%). Thus, the treatments with an U-shaped cross-section were more effective on water-saving and reducing deep percolation than those with a flat cross-section when using the same spacing width.

As conclusion, a spacing width of 10 cm is appropriate for the greenhouse celery cultivation using flood irrigation with about 40 mm water per irrigation event. The larger the spacing width is, the less the efficacy on water-saving and reducing deep percolation will be. Especially in the situation of flat film strip cross-section with large spacing width, such as T2, its efficacy was very little compared with other treatments of SFSP. The treatments with U-shaped cross-section had better efficacy even if the spacing was large. For instance, T4, U-shaped cross-section with a 40 cm spacing, had an efficiency similar to T3, flat cross-section and with a spacing of 10 cm.

SFSP had a great effect on the distribution of soil water content. Fig. 4 shows the comparisons between non-film treatment and various SFSP treatments on the distribution of horizontal average water content along the depth after the fourth irrigation event. The horizontal average water content refers to the average value of water contents of soil above film strips and above spacing width at the same depth. For the hori-

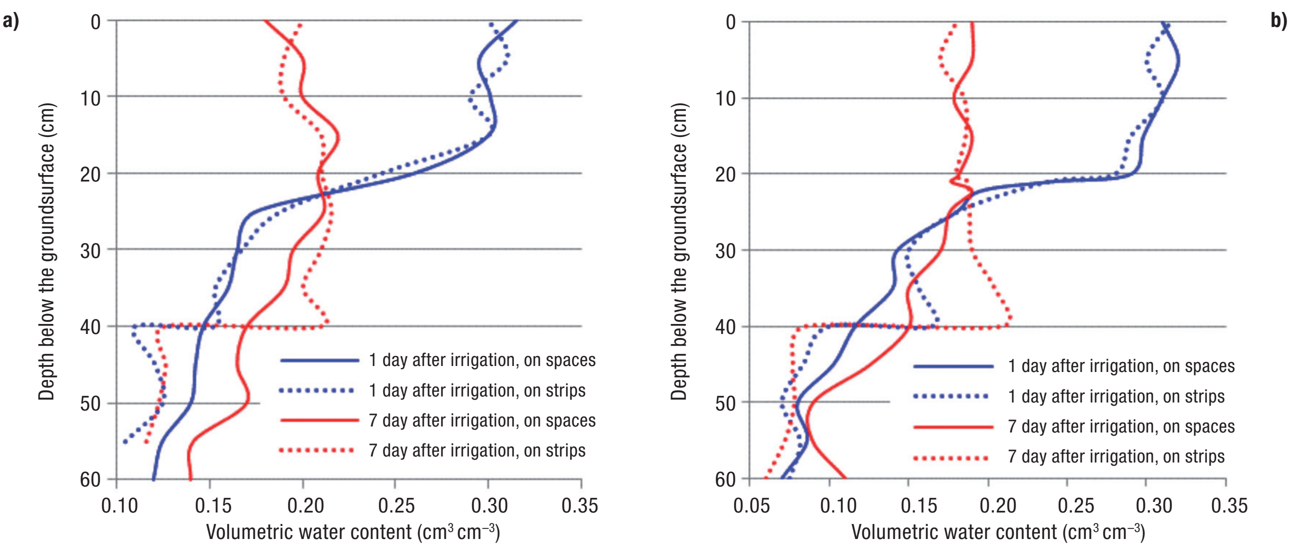

Figure 5. Water content distributions of soil above film strips and above spacing areas along the depth for treatments T3 and T5 after fourth irrigation: a) treatment T3, b) treatment T5

zontal average water content after the same time from irrigation, it is higher after placing film strips than before placing film strips. The differences of horizontal average water content distribution along the depth at the same time after irrigation between various treatments were not obvious.

Experimental results show that SFSP can cause differences in water content distribution along the horizontal direction. Fig. 5 shows that, in comparison with the water content distribution along the depth of sampling points at the middle of cross-section of film strips and that at the middle of spacing areas, the differences at the same depth continuously change with the extension of time after irrigation. The situations in T2 & T4 are similar (Fig. 5).

In general, the water content at the same depth above the film strips was higher than that above the area between the spacings; however, such difference is very small in the range of 0-20 cm depth for various treatments of SFSP. Obvious differences occurred only in the soil layer of 20-40 cm, so the situation of the uneven distribution of water content along horizontal did not have impact on the celery's growth.

In summary, in greenhouse vegetable cultivation, SFSP could reduce deep percolation and save irrigation water. With proper SFSP layout variables, the water content of root layer could be controlled within an appropriate range. The cross-section of film strips placed underground could be selected from two different cross-sections, *i.e.* flat and U-shaped, the latter is more effective in reducing the deep percolation. The effect was greater for smaller spacings between strips.

The average water content was higher after placing subsurface film strips, and result in water content differences between the soil above strips and in between areas. Precaution should be exercised to avoid excessive differences in soil water content to impact the celery's growth. Irrigation system design tends to be affected by local soil and climatic conditions, and layout variables tested here are only valid for the study case; and for other areas or crops, more field tests are needed.

Acknowledgements

This work was made possible with funding from scientific research key project of the Ministry of Education of P.R.C., grant No. 02084 awarded to Dr. Longtan Shao. We are very grateful to Dr. Lijia An, for his support and co-operation in the field work.

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