INTEGRATION OF SUBSURFACE IRRIGATION AND ORGANIC MULCHING WITH DEFICIT IRRIGATION TO INCREASE WATER USE EFFICIENCY OF DRIP IRRIGATION

دمج الرى تحت السطحي والتغطية العضوية مع الرى الناقص لزيادة كفاءة استخدام المياه للرى بالتنقيط

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***Keywords:** deficit irrigation, subsurface drip irrigation, rice straw mulching, water use efficiency, tomato yield.*

ABSTRACT

This study aimed to integrate the ability of organic mulching (rice straw) and subsurface irrigation with deficit irrigation to save soil moisture content (SMC) and increase water use efficiency (WUE). A field experiment was carried out during 2019 on tomato crop in sandy soil. The variables included four levels of irrigation namely 70, 80, 90, and 100% of crop evapotranspiration (ET_c) with three irrigation techniques which were subsurface drip irrigation (SSD), mulched surface drip irrigation (MD), and mulched subsurface drip irrigation (MSSD). The treatments of MSSD showed earlier maturity of tomato crop and longer picking period if compared to MD and SSD treatments. MSSD showed higher ability to save (SMC) than other irrigation techniques. Reduction of applied water from 100 to 70% ET_c led to a decrease in tomato yield by 23.32% at MSSD compared to 28.47%, and 26.23% for MD, and SSD respectively. The highest WUE was at MSSD70 with 5.92 kg/m^3 while the least was 4.21 kg/m^3 with SSD100. The highest benefit/cost ratio was 9.03 with the treatment SSD70 while the highest profit of water unit was 2.19 US\$/m^3 with MSSD70. MSSD can be used with 90% of ET_c without any significant difference in tomato crop while it can be used with 70% ET_c to obtain higher WUE. The study recommended integrating rice straw mulching and subsurface drip irrigation with deficit irrigation as a strategy to save irrigation water and obtain the maximum possible benefits of water unit whether related to tomato yield or its revenue.

ملخص

تهدف هذه الدراسة الى دمج قدرة التغطية العضوية (قش الأرز) والرى التحت سطحي مع الرى الناقص في المحافظة على المحتوى الرطوبي للتربة لزيادة كفاءة استخدام المياه. تم اجراء تجربة حقلية خلال عام 2019 على محصول الطماطم في تربة رملية. شملت المتغيرات أربعة مستويات من مياه الرى وهى 90،80،70، 100% من الاستهلاك المائي للمحصول باستخدام ثلاث تقنيات للرى وهى الرى بالتنقيط التحت سطحي والرى بالتنقيط السطحي مع التغطية بالإضافة للرى التحت سطحي المغطى. أظهرت معاملات الرى بالتنقيط التحت سطحي المغطى نمو مبكر لمحصول الطماطم وفترات حصاد أطول مقارنة بمعاملات الرى بالتنقيط السطحي المغطى والرى التحت سطحي. أظهر الرى بالتنقيط التحت سطحي المغطى قدرة أكبر على الحفاظ على المحتوى الرطوبي للتربة مقارنة بالتقنيتين الأخريين. تخفيض مياه الرى من 100% الى 70% من الاستهلاك المائي أدى الى نقص محصول الطماطم بنسب 23.32، 28.47، 26.23% من أعلى قيمة انتاجية تم الحصول عليها لكل من معاملات الرى تحت سطحي المغطى ، والسطحي المغطى، والرى التحت سطحي على الترتيب. بلغت أعلى قيمة لكفاءة استخدام المياه 5.92 كج/م^3 للرى التحت سطحي المغطى عند النسبة 70% بينما بلغت أقل قيمة لكفاءة استهلاك المياه 4.21 كج/م^3 للرى التحت سطحي مع النسبة 100% من الاحتياجات المائية للمحصول. بلغت أعلى نسبة عائد الى التكاليف 9.03 لمعاملة الرى تحت سطحي المغطى مع 70% من الاحتياجات المائية وحققت نفس المعاملة أقصى ربح من وحدة المياه وبلغ 2.19 دولار أمريكي /م^3. يمكن استخدام الرى تحت سطحي المغطى بقش الأرز مع النسبة 90% من الاستهلاك المائي للمحصول دون انخفاض محصول الطماطم بشكل معنوي ويمكن استخدام نفس التقنية مع النسبة 70% للخصول على كفاءة أعلى لاستخدام المياه. أوصت الدراسة بدمج التغطية بقش الأرز مع الرى التحت سطحي والرى الناقص كاستراتيجية للحفاظ على مياه الرى وتحقيق أقصى عائد من وحدة المياه سواء لإنتاج محصول الطماطم أو لتحقيق أفضل ربح مادي.

INTRODUCTION

Agricultural activities which are necessary to assure human needs withdraw about 70-95% of fresh water *(Evans and Sadler, 2008; FAO, 2012)*. Irrigated agriculture extends over 270 Mha and provides 40 to 45% of the world needs of food and fibers *(Douh and Boujelben, 2011)*. It is necessary to apply all possible strategies and techniques to achieve sustainability of water resources and agricultural production (*Morison et al., 2008*). Drip irrigation system as a modern irrigation system has the feature of saving irrigation water and obtaining higher yield which means higher water use efficiency *(Aujla et al., 2007; Ibragimov et al., 2007)*. In the way to maximize water use efficiency of drip irrigated crops; it is logic to think about how to reduce irrigation water loss to apply least possible amount of irrigation water in parallel with obtaining the maximum possible crop yield.

Deficit irrigation can appear as an acceptable solution to save irrigation water and obtain higher water use efficiency especially when the water resources are limited *(Kirda et al., 1999)*. On the other hand, water deficiency is an adverse aspect for crop production *(Wu et al., 2008)*. The studies made by (*Romero et al., 2004; Al-Omrana et al., 2005; García–Tejero et al, 2011; Çolaka et al., 2018; Mele, 2019; Abdelkhalik et al., 2020; Mattar et al., 2020)* proved that deficit irrigation leads to increase water use efficiency despite the reduction in crop yield if compared to full irrigation. Deficit irrigation should be regulated and well managed to minimize the reduction of crop productivity as possible. Using deficit irrigation requires minimizing the irrigation water loss especially evaporation from soil surface to ensure that the plant obtains greatest potential benefit from applied water.

Subsurface drip irrigation has the advantage of saving water if compared to surface drip irrigation *(Lamm and Trooien, 2003; Patel and Rajput, 2007; Badr et al., 2010; Abed EL-Hamied et al., 2017; Umair et al., 2019)*. The use of subsurface drip irrigation supports crop production process with many advantages like applying water and nutrients in the most sensitive part of the root zone, weed control, and dry soil surface which results in higher yield with minimal water loss *(Encisco et al., 2005; Lamm and Camp, 2007; Patel and Rajput, 2007; Patel and Rajput, 2008; Selim et al., 2009; Thompson et al., 2009)*.

Surface mulching whether using organic or inorganic materials gives the advantages of keeping soil moisture, reducing salts accumulation, and controlling weeds. Organic mulch has the ability to control soil temperature, improve physical and chemical properties of the soil, and enhance soil biological activity *(Deng et al., 2006; Ramakrishna et al., 2006)* if compared to inorganic mulch *(Al-Wahaibi et al., 2007; Al-Rawahy et al., 2011)*.

Rice straw has the features of organic mulch beside its availability and low-cost in the local Egyptian agricultural environment, which causes avoidance of profits reduction resulted from the increase of total farming costs. (*Abo-Ogiala and Khalafallah, 2019)* mentioned that rice straw mulch could save 50% of water requirements of grapes because of its role in saving soil moisture. (*Abdel-Raouf and Ragab, 2018)* studied the effect of using deficit irrigation and rice straw mulching with partial root drying strategy for maize crop irrigated with drip irrigation system. Their results indicated that rice straw mulching helped to obtain higher water use with deficit irrigation due to the ability of retaining soil moisture and reducing evaporation loss.

Integration of subsurface irrigation and organic mulching with deficit irrigation is expected to increase the benefits of saving irrigation water for each technique more than if they are used individually.

Applying this proposed integration to a highly drought-sensitive crop like tomato *(Shao et al., 2015; Cui et al., 2020)* is expected to demonstrate the effect of using less amounts of irrigation water on crop yield and water use efficiency clearly. The aim of this study is using deficit irrigation and integrating it with subsurface irrigation and rice straw mulching to investigate for which level they can reduce the effect of water stress on tomato crop yield in order to obtain higher water use efficiency with drip irrigation system.

MATERIALS AND METHODS

Description of the study area and agronomic practices

Field experiment was carried out in a private farm (30.32°N, 30.63°E) in Khataba village, Menoufia governorate, Egypt under sandy soil conditions. Table 1 shows the physical properties of the experiment soil. Tomato crop (super strain, B) was cultivated during the summer season of the year 2019. Tomato seedlings were transplanted in the middle of February and then moved to the permanent soil on April 5th.

Table 1

Some physical properties of the experiment soil

Depth, [cm]	Particle size distribution, [%]			Texture	Field capacity, [%]	Permanent wilting point, [%]
	Sand	Silt	Clay			
0-15	89.94	0.45	9.61	Sandy	9.8	4.8
15-30	89.71	0.45	9.84	Sandy	10.2	5.0
30-45	88.51	3.24	8.28	Sandy	10.9	5.1
45-60	87.82	4.22	7.96	Sandy	11.5	5.5

Table 2 shows chemical characteristics of irrigation water while chemical properties of the experiment soil are listed in Table 3. The experiment area was ploughed two times before planting; each of them was perpendicular to the direction of the other. Organic manure and super phosphate were added to the soil during ploughing in rates of 72 m^3/ha, and 960 kg/ha respectively. Application of fertilizers to the soil was made through fertigation technique by adding fertilizers with required amounts to the fertilizers tank of the farm which was connected to the irrigation network. 720 kg/ha of ammonia sulphate and potassium sulphate were added in three batches with irrigation water starting from the first irrigation process with 20 days interval. The level of soil surface was completely horizontal with no slope.

Table 2

Chemical properties of irrigation water

EC, [dS/m]	Cations, [m_{eq}/l]					Anions, [m_{eq}/l]		
	pH	Na	K	Ca	Mg	HCo_3	Cl	SO_4
0.41	7.5	2.3	0.3	2.3	2.1	0.6	3.9	2.4

Table 3

Some Chemical properties of experiment soil

EC, [dS/m]	pH	Organic matter, [%]	CaCo3, [%]
4.2	7.68	0.69	27

Experimental design and layout

The variables of this study included four levels of irrigation (*IL*) namely 100, 90, 80, and 70% of crop evapotranspiration *(ET_c)* and three drip irrigation techniques (*IRT*) which were subsurface drip irrigation *(SSD)*, mulched surface drip irrigation (*MD*), and mulched subsurface drip irrigation *(MSSD)*. The statistical design was split-plot. Drip irrigation technique was the main plot while the irrigation level was sub-plot with three replicates for each treatment. Statistical analysis and Duncan's means comparison test was carried out using Cropstat 7.0 and MstatC computer software, respectively.

Dimensions of the experiment area were 70m length and 50m width. The layout of the experiment was as shown in Figure 1.

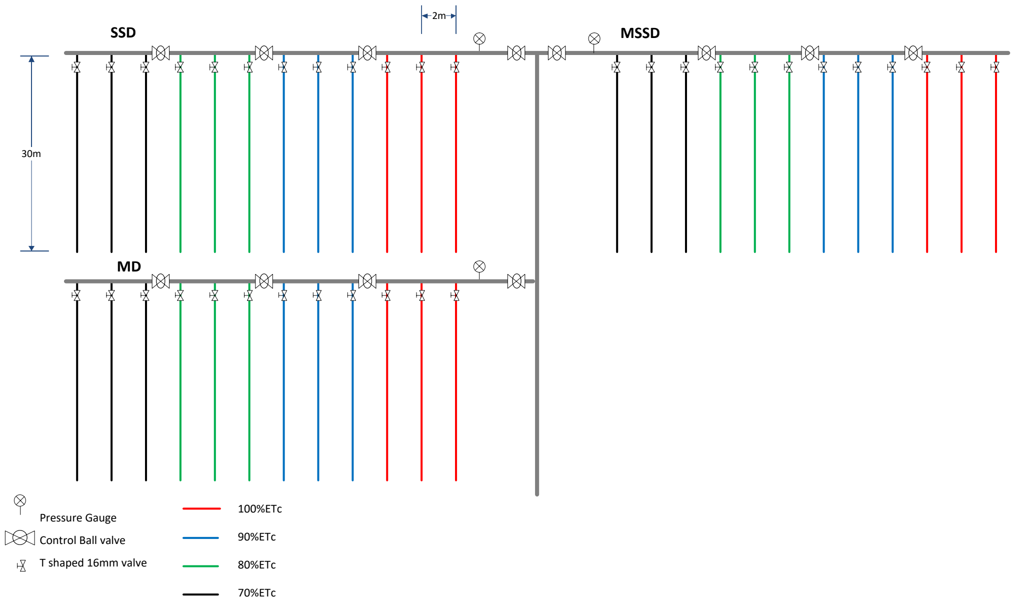


Fig. 1– Schematic drawing for the layout of experiment and irrigation network

Manifolds were PVC pipes with 63mm inner diameter. Polyethylene laterals 30m long and 16mm inner diameter had built-in emitters with 50 cm spacing. Laterals spacing was 2m. Subsurface drip irrigation laterals were laid manually at 20 cm depth from soil surface.

The beginning of each lateral was provided with T-shaped 16mm plastic valve and the end of each lateral was closed by an end cap. Rice straw covered the whole length of mulched treatments' laterals with a rate of 0.3 kg/m^2. The operating pressure of the irrigation network was 200 kPa and the irrigation frequency was every 72 hours. Irrigation treatments started after moving seedlings to the permanent soil.

Crop water requirement

Crop water requirement was calculated basing on climate data collected from Tahrir meteorological station (30.70ºN, 30.65ºE) which covers the experiment area. Table 4 shows the used climate data during the growing season. FAO Cropwat 8.0 computer program was used to calculate the reference evapotranspiration *(ET_o)*. Crop evapotranspiration *(ET_c)* was calculated according to Equation 1.

$$ET_c = ET_\circ . K_c \tag{1}$$

Where: K_c is crop coefficient.

Crop coefficient values of tomato were 0.6, 1.15, and 1.95 for initial, middle, and end of growing season respectively *(FAO, 1998).*

Table 4

Climate data and reference evapotranspiration (ET_o) values

	April	May	June	July	August
Minimum Temperature, [ºC]	11.40	14.10	17.50	19.50	19.40
Maximum Temperature, [ºC]	28.20	31.80	34.60	34.70	34.60
Sunshine hours, [h/day]	8.65	9.80	10.83	10.59	10.12
Wind speed, [m/s]	2.59	2.50	2.20	1.09	1.09
Solar radiation, [MJ/m^2/day]	21.67	24.48	26.2	25.69	24.10
Relative humidity, [%]	56.19	53.57	55.75	63.55	65.67
Precipitation, [mm/month]	2.00	0.00	0.00	0.00	0.00
ET_o, [mm/day]	4.42	5.39	5.94	5.65	5.26

Soil moisture content variation

The main purpose of measuring soil moisture content was to investigate the ability of each treatment to reduce soil moisture loss which is expected to help in reducing the possible negative effect of deficit irrigation on crop production. Soil moisture content was measured at 0, 12, 24, and 48 hours after irrigation. 3 cm diameter 4.5 cm height gypsum blocks were made using anti saline gypsum formula to measure the soil moisture content. Every gypsum block had two shielded steel cables 70 cm length which were immersed vertically in the blocks. 6 gypsum blocks were immersed horizontally under emission point with 10cm vertical spacing to measure the vertical distribution of soil moisture through 60 cm depth of the root zone as shown in Figure 2. Every cable had a label mentioning its measuring depth. The electric resistance between the two cables was used to describe the soil moisture content. The average of the readings of the six gypsum blocks described the soil moisture content of the root zone. Measurement of the soil moisture content was in one position in the middle of one lateral from each treatment

A calibration process has been made to detect the soil moisture content value facing each electric resistance. Twelve soil samples with a volume of 200 ml for each one were collected from the experiment area, and wetted with different amounts of water to make a variation in moisture content. The electric resistance reading was recorded and the soil moisture content was calculated using gravitational method. All the used gypsum blocks have been made with the same dimensions and materials.

Fig. 2– Soil moisture measurement using gypsum blocks

Crop yield and water use efficiency

Tomato crop harvesting of each treatment started when fruits reached the acceptable marketing size and color. The average yield of the three replicates described the total crop yield. Water use efficiency (WUE) described the tomato crop yield per volumetric unit of irrigation water. Water use efficiency was calculated referring to *Rodrigues and Pereira, 2009* as follows:

$$WUE = \frac{Y}{W_A} \tag{2}$$

Where: WUE is water use efficiency, [kg/m^3];
Y= Crop yield, [kg/ha];
W_A= Amount of applied water, [m^3/ha].

Profits

Total annual costs of agronomic practices and network operation were calculated referring to *Buchanan and cross, 2002*. The total costs were the summation of fixed costs and total variable costs. Fixed costs included annual depreciation of the irrigation network components, investment costs, and taxes and insurance. Scrap value was 10% of the initial cost of the network components. Annual interest ratio was 7.75% referring to the data of Egyptian Central Bank in 2019. Taxes and insurance was 2% of the initial cost.

Variable costs included the cost of repairs and maintenance, energy, labor, and any additive costs. Repairs and maintenance cost was considered to be equal to the total depreciation cost. The source of energy was diesel fuel with a price of 0.41 US$/l. Labor cost was 6US$/person/day with 8 hours daily working duration.

Additive costs included seeds and seedlings, rice straw, chemicals, agronomic practices and manual harvesting. Gross revenue of tomato crop was calculated to determine the benefit–cost (B/C) ratio. Total profits were divided by total applied water of each treatment to investigate the revenue of each unit of water volume. Referring to the Egyptian market and conversion price of US$ to Egyptian pound, the price of selling tomato from the farm after finishing harvesting was 0.37 US$/kg in average during the harvesting period.

RESULTS AND DISCUSSION

Growing season duration

Combining rice straw mulching and subsurface drip irrigation led to shorten the maturity period followed by mulched drip irrigation and subsurface drip irrigation, respectively. Data listed in Table 5 showed the total number of days of growing season including the time period after planting till reaching maturity stage (D_{mat}) and the duration of harvesting period (P_{har}). The results showed that rice straw mulching had an effect on accelerating the maturity of tomato fruit. Both mulched techniques had fewer days till reaching maturity if compared to subsurface drip irrigation treatments. The longest maturity period was at the treatment *SSD70* while the shortest was at *MSSD100* and *MSSD90* which was 56 days. The less amount of applied water, the longer maturity period observed.

These results might refer to the additional feature of rice straw mulching to make a modification to soil temperature beside saving water especially in early stage of tomato growing *(Yang et al., 2006; Abd El-Kader et al., 2010; Al-Rawahy et al., 2011)*. The treatment *MSSD100* showed the longest harvesting period by 98 days while the treatment *SSD70* had the shortest harvesting period by 52 days.

Table 5

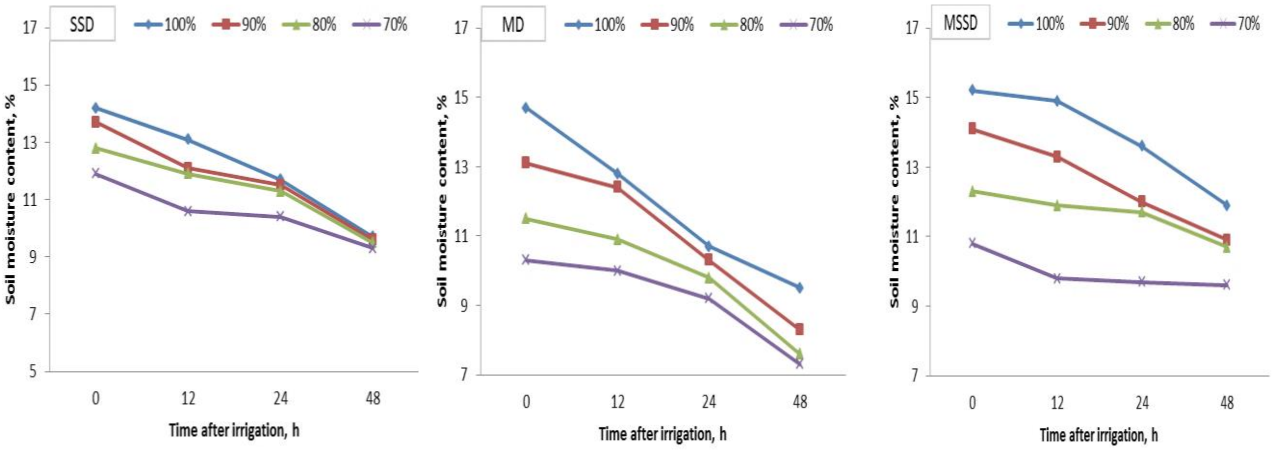
Number of days required to reach maturity and the total duration of harvesting period and growing season

***IL*, [% of ET_c]**	**SSD**			**MD**			**MSSD**		
	D_{mat}	**Total**	**P_{har}**	**D_{mat}**	**Total**	**P_{har}**	**D_{mat}**	**Total**	**P_{har}**
70	74	126	52	68	130	62	61	131	70
80	71	126	53	66	131	75	58	135	77
90	67	138	71	62	142	80	56	147	91
100	65	148	83	58	150	92	56	154	98

Soil moisture content variation

The integration between rice straw mulching and subsurface drip irrigation showed the highest ability to save soil moisture content and reduce its loss. The average values of soil moisture content during 48 hours revealed that reducing amount of applied water will reduce the loss of soil moisture. These results were in agreement with the results of (*Wang et al., 2012*). Figures 3 and 4 showed the variation of soil moisture content for different *IRT*s and *IL*s. There was a variation on initial soil moisture content after irrigation directly with the same amounts of applied water. This was due to a little variation in soil moisture content before irrigation despite the precautions taken to make this variation at minimum value. Any way this measurement was to evaluate the ability of each technique on saving moisture not to detect the moisture value itself. For subsurface drip irrigation; the rate of moisture loss in 100% amount was greater than other amounts. After 48 hours of irrigation, the values of soil moisture content were very close at all irrigation levels. The soil moisture content values of mulched drip irrigation indicated that the loss of soil moisture was greater than subsurface drip irrigation. Despite the ability of rice straw mulching to save water subsurface drip irrigation showed better ability to save irrigation water if compared to rice straw mulching because of the minimal evaporation loss from soil surface *(Abo-Ogiala and Khalafallah, 2019)*

Combining rice straw mulching and subsurface drip irrigation led to increase the benefits of the two techniques for saving water. In the *MSSD* treatments, the loss of moisture content at all levels of irrigation was less than the two other irrigation techniques. The soil moisture content of the treatment *MSSD70* was stable and nearly constant after 12 hours of irrigation till 48 hours. The minimum variation in soil moisture content was at the treatment MSSD70 while the maximum recorded variation was at the treatment MD100.



a) b) c)

Fig. 3– Soil moisture content at different irrigation techniques and irrigation levels

a. Subsurface drip irrigation; b. Mulched drip irrigation; c. Mulched subsurface drip irrigation

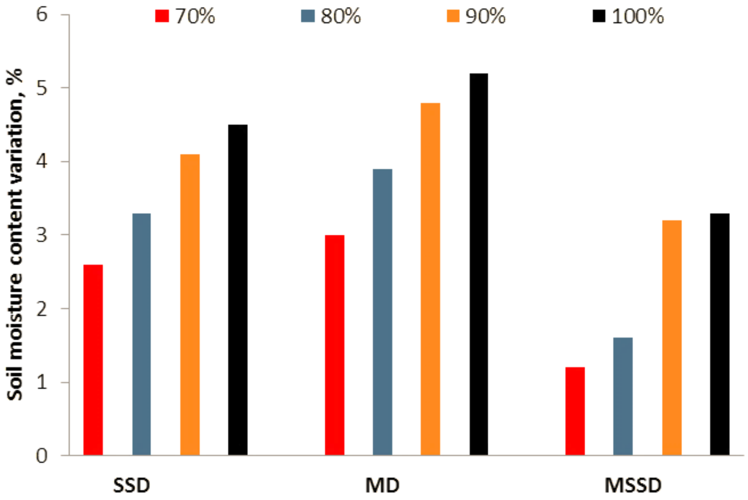


Fig. 4 – Comparison between soil moisture variation with different irrigation techniques and amounts of applied water after 48 hours of irrigation

Crop yield

The statistical analysis of the crop yield data showed that both of irrigation technique and irrigation level had a highly significant effect on tomato yield as shown in Table 6. The interaction between the two previously mentioned factors had no significant effect on crop yield. The non-significant effect of the interaction between irrigation technique and amount of applied water might be due to the effect of all proposed *IRT*s on reducing deficit irrigation impact on crop yield because of their ability to save moisture content.

Table 6

Analysis of variance for the effect of experimental variables on tomato crop yield.

Source of variation	DF	Sum of squares	Mean squares	F ratio
IRT	2	320.496	160.248	26.04**
IL	3	941.216	313.739	50.98**
IRT*IL	6	20.596	3.433	0.56 ns
Residuals	24	147.691	6.154	

***= Significant at 1% level; ns= not significant*

Tomato crop yield values listed in Table 7 clarified that tomato yield was directly proportional to the amount of applied water which was in agreement with the study of *Al-Ghobari and Deweidar (2018*) on tomato crop. The highest crop yield was 56.22 Mg/ha at *MSSD100* while the least obtained crop yield was 36.92 Mg/ha at *SSD70*. For all amounts of applied water, mulched subsurface drip irrigation gave the highest crop yield followed by mulched surface drip irrigation and the least values were with subsurface drip irrigation. Subsurface drip irrigation showed the ability of saving soil moisture content more than rice straw mulching; but rice straw mulching treatments recorded higher yield values because of the additive feature of modifying soil temperature. Reduction in the mount of applied water from 100 to 70% ET_c led to decrease the tomato yield by 23.32%, 28.47%, and 26.23% of the highest obtained yield with *MSSD*, *MD*, and *SSD* respectively. There was no significant difference between the treatments *MSSD100* and *MSSD90* while there was a significant difference between the same amounts of applied water with *MD* and *SSD*. This might clarify the effect of combining subsurface drip irrigation and rice straw mulching on reducing the effect of deficit irrigation on tomato yield when compared to using subsurface drip irrigation and mulched surface drip irrigation individually.

Table 7

Tomato crop yield, [Mg/ha] for the different irrigation techniques and levels

***IL*, [% of ET$_c$]**	**SSD**	**MD**	**MSSD**
70	36.92 g	38.13 g	43.11 ef
80	39.16 fg	44.95 de	48.76 cd
90	45.14 de	48.25 cd	52.38 abc
100	50.05 bc	53.31 ab	56.22 a

Least significant difference (L.S.D) at 5% level= 4.180

Amount of applied water and water use efficiency

Table 8 showed total amounts of applied water during growing season of each treatment and the values of WUE. The largest amount of applied water was 12405.72 m^3/ha for the treatment *MSSD100* while the least amount was 6982.92 m^3/ha for the treatment *SSD*70. The variation between same irrigation levels with different *IRT*s was because of the previously mentioned difference in growing season duration between treatments.

Table 8

Amount of applied water, [m^3/ha] and Water use efficiency, [kg/m^3] for different treatments

***IL*, [% of ET$_c$]**	**SSD**		**MD**		**MSSD**	
	W$_A$	**WUE**	**W$_A$**	**WUE**	**W$_A$**	**WUE**
70	6982.92	5.29 bcd	7225.93	5.28 bcd	7286.69	5.92 a
80	7980.48	4.91 de	8327.64	5.40 bc	8466.50	5.76 ab
90	9915.37	4.55 efg	10227.82	4.72 ef	10618.37	4.93 cde
100	11884.98	4.21 g	12145.35	4.39 fg	12405.72	4.53 efg

Least significant difference (L.S.D) at 5% level= 0.482

The highest water use efficiency was at *MSSD70* while the least was at *SSD100*. Deficit irrigation led to increase WUE for all treatments (*Abd El-Mageed and Semida, 2015; Zhang et al., 2017*). The only exception for this was the treatment *MD80* which gave higher WUE than *MD70* because of the significant difference between crop yield values of the previously mentioned treatments and lower water consumption difference if compared to the consumed water of the same two percentages with the other two irrigation techniques. Reducing amount of applied water from 100 to 70% ET_c led to increase water use efficiency by 30.68, 20.27, and 25.65% of the WUE value at 100% ET_c amount for *MSSD*, *MD*, and *SSD* respectively which recorded the least value of WUE at all *IRT*s. There are research evidences about the ability of deficit irrigation to show higher water use efficiency values, especially if the moisture stress resulting from the deficit is not so severe (*Igbadun et al., 2006; Saad et al., 2018*). The question appeared here which irrigation technique helped to get the benefits of deficit irrigation for increasing WUE. *MSSD* showed higher ability to get the best benefit of unit of water if compared to *MD* and *SSD*. This feature may help to use deficit irrigation in arid areas and all cases of limited water resources when saving water is more important than the obtained yield as recommended by *García–Tejero et al., (2011)*.

There was no significant difference between the WUE values of the treatments *MSSD70*, and *MSSD80* which had the highest value of WUE. There was no significant difference between WUE values for the other two irrigation techniques with the same amount of applied water. This result clarified the ability of the three *IRT*s to increase water use efficiency with deficit irrigation by keeping the reduction in tomato crop yield at minimum possible level with a clear distinction for the integration between subsurface and rice straw mulching with deficit irrigation.

Table 9 showed the analysis of variance for the effect of different *IRTs* and *ILs* on water use efficiency. Both of irrigation technique and amount of applied water had a highly significant effect on water use efficiency. Despite the clear variation in amounts of applied water for different treatments but the interaction between the *IRT* and IL did not show a significant effect on water use efficiency. This might also clarify the role of the experimental *IRTs* in reducing the negative effect of water stress on tomato crop yield.

Table 9

Analysis of variance of the effect of experimental variables on water use efficiency

Source of variation	**DF**	**Sum of squares**	**Mean squares**	**F ratio**
IRT	2	1.82	0.91	11.13**
IL	3	7.44	2.48	30.29**
IRT*IL	6	0.46	0.076	0.93 ns
Residuals	24	1.96	0.082	

***= Significant at 1% level; ns= not significant*

Profits

The main differences in costs between all treatments were due to the costs of energy, labor, and mulching. For all irrigation techniques, the total costs followed a descending order with the amounts 100, 90, 80, and 70% ET_c respectively, as shown in Table 10. This was due to the longer operation time period which increased energy consumption.

Total costs of rice straw mulched drip irrigation were higher than the treatments of subsurface drip irrigation. This is due to the additional costs of mulching material and longer growing season which needed more energy and labor (*Tiwari et al., 2003*). The treatments of MSSD had the highest costs when compared to the corresponding treatments at both *SSD* and *MD*. The maximum benefit was *20801.4* US$/ha for the treatment *MSSD100* while the least one was 13660.4 US$/ha for the treatment SSD70. The highest B/C ratio was 9.03 for the treatment SSD80 while the least one was 7.91 for the treatment MD70. Despite the higher tomato yield of *MSSD* compared to *MD* and *SSD*, it did not record the highest B/C ratio. This was mainly due to the costs of burying drip laterals, rice straw mulching, longer season which meant higher costs for energy and harvesting labor.

The maximum B/C ratio for *MSSD*, *MD*, and *SSD* were at the percentages 80, 90, and 80% ET_c respectively. The previous result pointed out to the ability of the three techniques to be profitably integrated with deficit irrigation regardless the different recommended percentage of water stress for each one. The reduction in the amount of applied water from 100 to 70%ET_c led to decrease the benefits of *MSSD*, *MD*, and *SSD* by 23.32%, 28.47%, and 26.23% of maximum benefit at each irrigation technique respectively. The less difference in benefits at *MSSD* referred to the less difference in crop yield with this irrigation technique. The profits of water unit pointed out that the maximum obtained profit of water unit was 2.19 US$/m3 for the treatment *MSSD70* while the least one was 1.56 US$/m^3 for *SSD100*. The maximum water profit for *MD* was 2.0 US$/m^3 with 80% ET_c ratio while it was 1.96 US$/m^3 for *SSD* with 70% ET_c ratio. This also confirmed the ability of the three techniques to maximize the profits of water unit when implementing deficit irrigation with a rational advantage for the combination between rice straw mulching and subsurface drip irrigation to be integrated with deficit irrigation.

Table 10

Total annual costs and benefits of tomato crop during the growing season, [US$/ha]

	SSD				***MD***				***MSSD***			
	70	***80***	***90***	***100***	***70***	***80***	***90***	***100***	***70***	***80***	***90***	***100***
Total fixed costs	360.26	360.26	360.26	360.26	360.26	360.26	360.26	360.26	360.26	360.26	360.26	360.26
Energy	14.92	25.03	36.76	43.80	15.96	26.31	37.66	44.20	15.98	26.84	38.27	44.55
Labor	936.00	954.00	1278.00	1494.00	1116.00	1350.00	1440.00	1656.00	1260.00	1386.00	1638.00	1764.00
Repairs and maintenance	116.64	116.64	116.64	116.64	116.64	116.64	116.64	116.64	116.64	116.64	116.64	116.64
Additives	92.81	148.14	231.99	271.20	175.37	212.14	226.29	260.23	198.00	217.80	257.40	277.20
Total variable cost	1160.37	1243.81	1663.39	1925.64	1423.97	1705.09	1820.58	2077.07	1590.62	1747.28	2050.31	2202.39
Total cost	1520.63	1604.07	2023.65	2285.90	1784.23	2065.35	2180.84	2437.33	1950.88	2107.54	2410.57	2562.65
Benefits	13660.4	14489.2	16701.8	18518.5	14108.1	16631.5	17852.5	19724.7	15950.7	18041.2	19380.6	20801.4
B/C ratio	8.98	9.03	8.25	8.10	7.91	8.05	8.19	8.09	8.18	8.56	8.04	8.12
Water profits US$/m^3	1.96	1.82	1.68	1.56	1.95	2.00	1.75	1.62	2.19	2.13	1.83	1.68

CONCLUSIONS

Combining rice straw mulch with subsurface drip irrigation had a significant effect on crop yield and water use efficiency with deficit drip irrigated tomato. Using rice straw mulching with subsurface drip irrigation impacted on saving soil moisture content especially at 70, and 80% ET_c. This feature helped to speed crop maturity and increase crop yield with all *MSSD* amounts of applied water. Both of irrigation technique and amount of applied water had a highly significant effect on crop yield and water use efficiency. The previously mentioned factors showed no significant effect of the interaction between them neither on crop yield nor on water use efficiency. Deficit irrigation can be used till 90% ET_c with *MSSD* without any significant difference on crop yield. In order to obtain the maximum WUE; *MSSD* can be used with 70% ET_c. The maximum B/C ratio was at the treatment *SSD80* while the maximum profit of water unit was at *MSSD70*. Future studies are recommended to use *MSSD* on crops less sensitive to water stress as it is expected to use higher deficit irrigation levels. Also there is a need for more studies on the integration between subsurface drip irrigation, rice straw mulch, and deficit irrigation on different crops in different soil types and climate conditions especially in arid areas where water supplies are limited, in order to maximize the benefits of water unit whether related to crop yield production or economic profits.

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