Iraqi Journal of Market Research and Consumer Protection
(2024) 16(1): 197-209
DOI: http://dx.doi.org/10.28936/jmracpc16.1.2024.(17)

المجلة العراقية لبحوث السوق
وحماية المستهلك

EVALUATING THE PERFORMANCE OF DIFFERENT SOLAR IRRIGATION SYSTEMS AND THEIR EFFECT ON BEAN YIELD (*Vicia Faba… L)*

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Received 25/ 5/ 2023, Accepted 21/ 6/ 2023, Published 30/ 6/ 2024

ABSTRACT

An experiment was carried out at Al-Raed Research Station, which is located on the Baghdad-Anbar Road. It was conducted during the winter season of 2022-2023, in order to evaluate the performance of different solar irrigation systems and their effect on bean yield (*Vicia faba… L*). A randomized complete block design (RCBD) was used with three replications. The experiment consists of three factors. first factor was the solar panel type with two levels: mono-crystalline and poly-crystalline. Second factor was the irrigation system with two levels: drip and sprinkler irrigation system. The third factor was the distances between the sub-lines with three levels (40, 60, 80 cm). The results show that the monocrystalline achieved the best result by achieving the highest irrigation system efficiency (76.31%), and highest seeds yield total (6618 Kg/ha) with minimum operational costs (0.0252 $/KWh). The drip irrigation had the highest irrigation system efficiency (84.40%), and highest total seeds yield (6077 Kg/ha) with minimum operational costs (0.0340 $/ KWh). The distance (40cm) between the sublines had the highest irrigation system efficiency (76.83 %), with less operational costs (0.0398 $ / KWh).

key words: solar panels, seed yield, operational costs, drip irrigation.

[*] **The research is taken from a master's thesis by the first researcher.**

تقييم أداء أنظمة ري مختلفة تعمل بالطاقة الشمسية وتأثيرها على إنتاجية الباقلاء (*Vicia Faba…L*)

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الخلاصة

نفذت تجربة في محطة ابحاث الرائد الواقعة على طريق بغداد - الانبار خلال فصل الشتاء للموسم (2022-2023) لدراسة تقييم أداء أنظمة ري مختلفة تعمل بالطاقة الشمسية وتأثيرها على إنتاجية الباقلاء (*Vicia faba L*). تم استخدام تصميم القطاعات الكاملة المعشاة (RCBD) بثلاثة مكررات. تتكون التجربة من ثلاثة عوامل. كان العامل الأول هو نوع الألواح الشمسية بمستويين: أحادي البلورية ومتعدد البلورات. العامل الثاني كان نظام الري ذو مستويين نظام الري بالتنقيط والرش والعامل الثالث كان المسافات بين الخطوط الفرعية بثلاثة مستويات (40، 60، 80 سم) تم دراسة المؤشرات التالية: كفاءة نظام الري (٪)، مجموع محصول البذور. (كغم / هكتار)، تكاليف التشغيل (دولار/ ك.و.س). أظهرت النتائج أن أحادي البلورية حقق أفضل نتيجة من خلال تحقيق أعلى كفاءة لنظام الري (76.31٪)، وأعلى مجموع محصول للبذور (6618 كغم / هكتار) بأقل تكاليف تشغيلية (0.0252 دولار / ك.و.س). حقق الري بالتنقيط أعلى كفاءة لنظام الري (84.40٪)، وأعلى مجموع محصول للبذور (6077 كغم / هكتار) بأقل تكاليف تشغيلية (0.0340 دولار/ ك.و.س). كان للمسافات بين الخطوط الفرعية أعلى كفاءة لنظام الري (76.83٪)، مع تكاليف تشغيل أقل (0.0398 دولار/ ك.و.س).

الكلمات المفتاحية: الألواح الشمسية، حاصل البذور، تكاليف التشغيل، ري بالتنقيط.

INTRODUCTION

Human erroneous practices are considered one of the most important negatives that affect the environment and contribute to the raising rates of degrees in heat, which has contributed in the phenomenon of global warming that Iraq and the region in general suffer from **(Mahal *et al.*, 2022)**. The performance efficiency of the solar panel is one of the most important characteristics that give an indication to the quality of the solar panel, but it is affected by a number of factors, with the weather being the most influential, due to its close association with the amount of radiation reaching the panel (**Zeinaldeen, 2020)**. The use of modern irrigation systems can provide water in appropriate quantities for plants, in addition to reducing waste in irrigation water more than other irrigation systems (**Rasheed, 2021)**. Enhancing the efficiency of irrigation systems is one of the objectives that the researchers seek in order to increase the areas planted with crops and the main waist for local consumption while reducing the consumption of water resources **(Abdullah & Kadhim, 2023**). Attention to the calculations related to irrigation is one of the important things for the design and operation of irrigation projects (**Al-Kazragy, 2020)**. Increasing the productivity of agricultural crops is an objective pursued by farmers all over the world and this can be achieved by using modern irrigation methods **(Al-Lami *et al.*, 2023)**. In light of the scarcity of water, water recycling is one of the solutions that reduce pressure on water sources and is used to irrigate agricultural lands (**Rahi & Faisal, 2019)**. The use of traditional irrigation methods is one of the wrong practices by farmers, and this is due to the low operational costs compared to modern irrigation systems (**Karim & Karim, 2020).** The sprinkler irrigation system can be considered as one of the modern irrigation methods that can be used to reduce the amount of water wasted by traditional methods and a goal to achieve security food (**Al-Mehmdy & Yacoub, 2019**). The drip irrigation system and the sprinkler irrigation system can also be considered as modern irrigation systems that have a role in rationing water waste, but the drip irrigation system is more efficient than the sprinkler system **(Khattab & El-Housini, 2019)**. The plant density significantly affected all the studied traits **(Khalaf & Hassan, , 2022).** Through a study showed that the distance between 25 cm the plants were significantly superior and gave the highest average seed yield (**Sadiq & Mohammed, 2022)**.

Research problem

Due to the challenges faced by most parts of the world, including our dear country, from the threat to food security as a result of population increase and problems related to providing the necessary water for irrigation, in addition to the obstacles to providing the energy sources necessary for the operation of various irrigation systems, and what the world in general and our country Iraq in particular is experiencing from the greenhouse effect caused by the continuous and increasing use of fossil fuel derivatives as an energy source, the subject of the research came up.

Research objective

1. Comparison the performance of two types of solar panels.
2. Comparison of modern irrigation systems (drip, spray).
3. Comparison of the effect of the variation of distances between the sub-lines on the yield of the crop.

Thus: finding the best combination between the type of solar panel and the irrigation system and the best distance between the sab-lines on the productivity of the Faba bean crop.

MATERIALS AND METHODS

An experiment was carried out at Al-Raed Research Station, which is located on the Baghdad-Anbar Road. It was conducted during the winter season of 2022-2023. in order evaluate the performance of different solar irrigation systems and their effect on bean yield (*Vicia faba… L*). A randomized complete block design (RCBD) was used with three replications. The experiment consists of three factors. first factor was the solar panel type with two levels: mono-crystalline and poly-crystalline. Second factor was the irrigation system with two levels drip and sprinkler irrigation system and third factor was the distances between the sublines with three levels (40 , 60 , 80 cm) The following traits were studied : irrigation system efficiency (%), total seeds yield (Kg / ha), and operational costs ($/ KWh). A number of agricultural operations were carried out to prepare the experimental field, the field was flooded with water, and we waited for 20 days for the field to dry completely. Because of the density of the Jungles that the Experimental field suffers from. After completing the plowing process, the rotary plow was used to smoothen the previously ploughed soil, after which the levelling and adjustment machine was used. A group of samples were taken from the experimental field on 5/9/2022 and sent to the laboratories of the National Centre for Water Resources Management for soil analysis and to determine the physical and chemical characteristics of the experimental field as shows in Table (1). The bean crop was seeded manually at a depth of 3-5 cm, two seeds in each hole, at a distance of 25 cm between one hole and another, on 15/10/2022, weeds were removed manually and chemically.

Table (1): Physical, chemical and hydraulic preparties of the soil before planting

Soil depth	**Soil articulations $g.kg^{-1}$**			**Soil texture**	**Field volumetric water content at 33 Kps (Cm^3Cm^{-3})**	**Volumetric water content at 1500 Kps (Cm^3Cm^{-3})**	**PH**	**EC $dS.m^{-1}$**	**soil bulk density $Mg.m^{-3}$**
	sand	silt	Clay						
0 – 25	12	52	35	Silty clay loam	0.465	0.265	7.7	8	1.27
25 - 50	11	51	36	Silty clay loam	0.470	0.274	7.4	16	1.31

Characters Studied

irrigation system efficiency (%).

The efficiency of the two irrigation systems was measured according to the equations and methods used before (Al-Taif & Al-Hadithi, 1988).

$Ee = Ea \times Ed \times 100$…………… (1)

Where: -

Ee = Irrigation system efficiency %.

Ea = Perfusion efficiency %.

Ed = distribution efficiency %.

Perfusion efficiency was measured by the following equation:

$Ea = \left(\frac{Ws}{Wf}\right) \times 100$……………… (2)

Where: -

Ea = Perfusion efficiency%

Ws = the depth of water stored in the root zone (m).

Wf = The amount of Water received from the source (m).

Distribution efficiency was measured by the equation:

$Ed = \left(\frac{1-\bar{y}}{đ}\right) \times 100$…………….. (3)

Where: -

Ed = water- distribution efficiency %.

$\bar{Y}$ = average numerical deviation in depth of water stored from average depth stored during the irrigation (cm).
$\bar{d}$ = average depth of water stored during the irrigation (cm).

Total Seeds Yield (Kg / ha).

The bean crop was harvested on 3/16/2023, and the productivity was calculated on the basis of the first pound and on the basis of the average seed weight yield of three randomly selected plants from the beginning, middle and end of the experimental unit line multiplied by the plant density and then converted to ($Kg.ha^{-1}$), (**Al-Sahoki & Jiyad, 2023**).

Operational Costs ($ / KWh).

Operational costs were calculated on the basis of the energy unit (KWh), where the maximum power was measured during the operating condition and converted (Kw) and multiplied by the number of operating hours during the season, then divided the purchase price by (KWh), using the following formulas **(Maurya *et al*.,2015; Manfaluthy *et al*.,2021).**
The price per watt was calculated using the following formula:

$$O\ c = \frac{PP}{P_{mas}} \ \ldots\ldots\ldots\ldots\ldots\ldots \ (4)$$

Where: -
O c = Operational costs ($/KWh).
PP = purchase price ($).
P_{max} = Maximum Power (KWh).
The power was calculated with the following equation:

$$Pmax = Vmp \times Imp \ldots\ldots (5).$$

Where: -
P_{max} = Maximum Power (Watt).
V_{mp} = Maximum Power Voltage (Volt).
I_{mp} = Maximum Power Current (Ampere).

RESULTS AND DISCUSSION:

Irrigation System Efficiency (%).

Table 2 show the effect of the type of solar panels on the efficiency of the irrigation system as a percentage. It is clear that there is no significant effect of the type of solar panels used on the studied characteristic, as the monocrystalline solar panels recorded the highest average values for the efficiency of the irrigation system were (76.31%), while the polycrystalline solar panels recorded the lowest average values for the efficiency of the irrigation system (74.96%).

The results also indicated in Table 2 the effect of the type of irrigation system used on the efficiency of the irrigation system in percent, as the results showed a significant effect of the type of irrigation system used on the efficiency of the irrigation system in percent, as the drip irrigation system recorded the highest. The average values of the efficiency of the irrigation system were (84.40%), while the sprinkler irrigation system (Sprinkler) recorded the lowest average efficiency by (66.87%).

Table 2 also showed the effect of the environmental distances between the sub-lines on the efficiency of the irrigation system in percentage, as the results showed that there was no significant effect of the distances between the sub-lines on the efficiency of the irrigation system. The distance (40 cm) recorded the highest efficiency rates of (76.83%), while the distance recorded (80 cm) the lowest average efficiency was (74.73%).

The results also indicated in Table 2 the effect of the bilateral interference between the type of solar panel and the irrigation system used on the efficiency of the irrigation system %. The results indicate that there is a significant effect of the interaction between the type of solar panel and the type of irrigation system used on the efficiency of the irrigation system %. The monocrystalline solar panel (with drip irrigation system) achieved the highest average values of irrigation system efficiency (88.85%), while the monocrystalline solar panel with sprinkler irrigation system recorded the lowest irrigation system efficiency rates It reached (63.77%).

It is noted from Table 2 the effect of the bilateral interference between the type of solar panel and the distances between the sub - lines on the efficiency of the irrigation system %, The results indicate that there is no significant effect of the interaction between the type of solar panel and the distances between the sub-lines on the efficiency of the irrigation system. The monocrystalline solar panel with a distance of (40cm) recorded the highest average values for the irrigation system efficiency % which amounted to (78.28%), while the polycrystalline solar panel with a distance of (80cm) recorded the lowest average values for the irrigation system efficiency %, which was (73.24%).

Table 2 showed us the effect of the bilateral interference between the type of irrigation system used and the distances between the sub-lines, as the results indicate that there is no significant effect of the bilateral interference between the type of irrigation system and the distances between the sub-lines that the drip irrigation system achieved (Drip) at a distance of (60cm) the highest rates of irrigation system efficiency in % amounted to (85.23%), while the sprinkler irrigation system recorded with a distance of (60cm) the lowest averages of the irrigation system's efficiency in % was (65.48%).

Table 2 shows the effect of the triple interference between the type of solar panel, the type of irrigation system used, and the distances between the sub-lines on the efficiency of the irrigation system. The results showed that there was no significant difference between the triple interference between the type of solar panel, the type of irrigation system, and the distances between the sub-lines on the efficiency of the irrigation system. The results indicated that the monocrystalline solar panel with the drip irrigation system at a distance of (40cm) achieved the highest average values for the irrigation system efficiency amounted to (90.89%), while the monocrystalline solar panel with the sprinkler irrigation system recorded at the distance (60cm), the least average efficiency was (60.90%).

Table (2): The effect of the type of solar panel, irrigation system, and distances between sub-lines on the efficiency of the irrigation system (%).

Type solar panel (C)	**Irrigation system (I)**	**Distances between sub-lines (D)**			**C * I**	
		40	60	80		
Polycrystalline	Sprinkler	72.58	70.06	67.27	69.97	
	Drip	78.16	82.48	79.22	79.95	
Monocrystalline	Sprinkler	65.67	60.9	64.74	63.77	
	Drip	90.89	87.97	87.68	88.85	
LSD $_{C*I*D}$		6.483 $^{N.S}$			LSD $_{C*I}$	4.977
C * D						
Type solar panel (C)		40	60	80	Average type solar panel	
Polycrystalline		75.37	76.27	73.24	74.96	
Monocrystalline		78.28	74.44	76.21	76.31	
LSD C* D		4.163 $^{N.S}$			LSD $_{C}$	4.33 $^{N.S}$
I * D						
Type of irrigation system (I)		40	60	80	Average type irrigation system	
Sprinkler		69.12	65.48	66	66.87	
Drip		84.53	85.23	83.45	84.4	
LSD $_{I*D}$		5.259 $^{N.S}$			LSD $_{I}$	4.856
D						
Distances between sub-lines (D)		40	60	80		
Average distances		76.83	75.35	74.73		
LSD $_{D}$		3.057 $^{N.S}$				

Total Seeds Yield (kg / ha).

Table 3 shows us the effect of the type of solar panel used on the total seeds yield (kg/ha), as the type of panel used had a significant effect on character of the total seeds yield (kg/ha), where the monocrystalline solar panel excelled by recording the highest. The average of the total seeds yield (kg/ha) was (6618 Kg/ha), while the average total seeds yield (kg/ha) was lower for polycrystalline solar panels by (4714Kg/ha). The reason may be due to the higher efficiency of the monocrystalline panel. of the polycrystalline board, which gives a better performance to the pump responsible for the irrigation systems.

Table 3 shows us the effect of the type of irrigation system used on the character of the total seeds yield (kg/ha), where the type of irrigation system used had a significant effect on the characteristic of the total crop yield (kg/ha). It drip irrigation system excelled with, the average values of the total seeds (yield 6077Kg/ha), while the sprinkler irrigation system recorded the lowest value of the averages for the studied trait amounted to (5255Kg/ha). The cause may be due to the fact that the drip irrigation system is rarely affected by weather factors, which has a positive impact on productivity.

Table 3 also show the effect of the distances between the sub-lines on the total seeds yield (kg/ha), as the distances between the sub-lines had a significant effect on the character seeds yield total (kg/ha), where the distance (60cm) recorded the highest value of the averages. The total seeds yield amounted to (6262 Kg/ha), while the distance (80 cm) recorded the lowest value of the relevant averages at (3950 Kg/ha).

Table 3 also shows the effect of the bilateral interference between the type of solar panels and the type of irrigation system on the total seeds yield (kg/ha). It is clear to us that the monocrystalline solar panel with the drip irrigation system had the highest average value of the total crop yield, which amounted to (7029 Kg/h), while the polycrystalline solar panel with sprinkler irrigation system achieved the lowest values of the averages of the studied characteristic was (4302 Kg/h). There was no significant interaction between the type of solar panel and the type of irrigation system used on the character of the total seeds yield (kg/ha).

Table 3 also showed us the effect of the bilateral interference between the type of solar panel and the distances between the sub-lines on the total seeds yield (kg/ha), where the bilateral interference between the type of the solar panel and the distances between the sub-lines did not have a significant effect on the characteristic of the total seeds yield (kg/ha). The monocrystalline solar panel with a distance of (60cm) had the highest average yield value of (7735Kg/ha), while the polycrystalline solar panel with a distance of (80cm) recorded the lowest average value of the total seeds yield was (3075 Kg /ha).

Table 3 shows us the effect of the bilateral interference between the type of irrigation system and the distances between the sub-lines on the total seeds yield (kg/ha) Where the table shows us that there is a significant effect of the bilateral interference between the type of irrigation system and the distances between the sub-lines on the character of the total seeds yield (kg/ha). The drip irrigation system with a distance of (40 cm) exceeded the highest average value of the total seeds yield in a record (7933 Kg/ha), While the sprinkler irrigation system at a distance of (80 cm) recorded the lowest values for the averages, the total seeds yield was (3525 kg/ha).

Table 3 shows the effect of the triple interference between the type of solar panel, the type of irrigation system used, and the distances between the sub-lines on the total seeds yield (kg/ha).The monocrystalline panels with the drip irrigation system (Drip) at a distance of (40cm) achieved the highest value for the seeds yield total rate of (9100Kg/ha), On the other hand, the polycrystalline board with the sprinkler system at a distance of (80 cm) recorded the lowest value for the total seeds yield rates, which amounted to (2717 Kg/ha). The triple interference did not have a significant effect on the studied trait.

Table (3): The effect of the type of solar panel, irrigation system, and distances between sub-lines on the total seeds yield (kg/ha).

Type solar panel (C)	**Irrigation system (I)**	**Distances between sub-lines (D)**			**C * I**
		40	60	80	
Polycrystalline	Sprinkler	3690	6500	2717	4302
	Drip	6767	5178	3433	5126
Monocrystalline	Sprinkler	5490	8800	4333	6208
	Drip	9100	6670	5317	7029
LSD $_{C*I*D}$		990.4 $^{N.S}$			LSD $_{C*I}$ 278.2 $^{N.S}$
C * D					
Type solar panel (C)		40	60	80	Average type solar panel
Polycrystalline		5228	5839	3075	4714
Monocrystalline		7295	7735	4825	6618
LSD C* D		691.5 $^{N.S}$			LSD $_{C}$ 210.6
I * D					
type of irrigation system (I)		40	60	80	Average type irrigation system
Sprinkler		4590	7650	3525	5255
Drip		7933	5924	4375	6077
LSD $_{I*D}$		710.1			LSD $_{I}$ 277.4
D					
Distances between sub-lines (D)		40	60	80	
Average distances		6262	6787	3950	
LSD $_{D}$		594.1			

Operational Costs ($ / kwh).

Table 4 shows the effect of the type of solar panel used on operating costs $/KWh. The results indicate that there is a significant effect of the type of solar panel used on the characteristic of operating costs $/KWh. The polycrystalline solar panel achieved the highest average operating cost value (0.0874$/KWh), while the monocrystalline solar panel achieved the lowest operating cost average values (0.0252$/KWh). the reason for the low operating costs of the monocrystalline panel may be due to the lower price of the panel compared to the peak capacity.

Table 4 indicates the effect of the type of irrigation system used on operating costs ($/KWh), the results indicate that there is a significant effect of the type of irrigation system used on the characteristic of operating costs $/KWh. where the sprinkler irrigation system achieved the highest operating cost rates (0.0786$/KWh), While the drip irrigation system achieved the lowest operating cost average values (0.0340$/KWh). The reason may be due to the stability of the moisture stability, which affects the time of the irrigation periods.

It is noted from Table 4 the effect of the distances between the sub-lines on the operating costs ($/KWh)., The results indicate to us that there is a significant effect of the distances between the branch lines on the characteristic of operating costs ($/KWh). As the distance (80cm) achieved the highest average values, operating costs amounted to (0.0725$/KWh), While the distance (40cm) achieved the least value for operating cost rates, it was (0.0398$/KWh). The reason may be due to the distance (40 cm) achieving the lowest operating cost values, due to the overlapping of the irrigation lines affecting the humidity levels.

Table 4 also shows the effect of the dual interference between the type of solar panel and the type of irrigation system used on the operating costs ($/KWh). The results indicate that there is significant effect of the dual interference between the type of solar panel and the type of irrigation system on the characteristic of operating costs ($/KWh), Where the polycrystalline solar panel with the sprinkler irrigation system achieved the highest average operating cost values (0.1247$/KWh). While the monocrystalline solar panel with the drip irrigation system achieved the lowest rates of operating costs (0.0179$/KWh).

Table 4 also indicated the effect of the bilateral interference between the type of solar panel and the distances between the sub-lines on the operating costs ($/KWh), The results indicate to us that there is a significant effect of the bilateral interference between the type of solar panel and the distances between the branch lines on the characteristic of operating costs ($/KWh). The polycrystalline solar panel at a distance of (80cm) achieved the highest values of average operating costs amounting to (0.1145$/KWh), While the monocrystalline solar panel with a distance of (40cm) achieved the lowest average operating cost values (0.0203$/KWh).

Table 4 also showed us the effect of the bilateral overlap between the type of irrigation system used and the distances between the branch lines on the operating costs ($/KWh), The results indicate to us that there is a significant effect of the bilateral overlap between the type of irrigation system used and the distances between the branch lines on the characteristic of operating costs ($/KWh). The sprinkler irrigation system at a distance of (80 cm) achieved the highest rates of operating costs amounting to (0.1053$/KWh), While the results indicate that the drip irrigation system with a distance of (40 cm) achieved the lowest rates of operating costs were (0.0288 $/KWh).

Table 4 shows us the effect of the triple overlap between the type of solar panel, the type of irrigation system used, and the distances between sub-lines on operating costs ($/KWh). The results indicate that there is a significant effect of the triple overlap between the type of solar panel, the type of irrigation system used, and the distances between the sub-lines on the studied characteristic. The polycrystalline solar panel with the sprinkler irrigation system at a distance of (80cm) achieved the highest average operating cost value of (0.1700$/KWh), While the monocrystalline solar panel with the drip irrigation system at a distance of (40cm) achieved the lowest rates of operating costs (0.0153$/KWh), The reason may be due to the achievement of the monocrystalline solar panel with the drip irrigation system at a distance of (40 cm). The technical specifications of the Monocrystalline panels and their harmony with the drip irrigation system, which is considered one of the most important metered water irrigation systems, and the interference of moisture at the closest distance between the agricultural lines reduces the irrigation time.

Table (4): The effect of the type of solar panel, irrigation system, and distances between sub - lines on the Operating costs ($/KWh).

Type solar panel (C)	**Irrigation system (I)**	**Distances between sub-lines (D)**			**C * I**	
		40	60	80		
Polycrystalline	Sprinkler	0.0760	0.1280	0.1700	0.1247	
	Drip	0.0423	0.0490	0.0590	0.0501	
Monocrystalline	Sprinkler	0.0253	0.0313	0.0407	0.0324	
	Drip	0.0153	0.0180	0.0203	0.0179	
LSD $_{C*I*D}$		0.004863			LSD $_{C*I}$	0.003998
C * D						
Type solar panel (C)		40	60	80	Average type solar panel	
Polycrystalline		0.0592	0.0885	0.1145	0.0874	
Monocrystalline		0.0203	0.0247	0.0305	0.0252	
LSD C* D		0.0036			LSD $_{C}$	0.0031
I * D						
type of irrigation system (I)		40	60	80	Average type irrigation system	
Sprinkler		0.0507	0.0797	0.1053	0.0786	
Drip		0.0288	0.0335	0.0397	0.0340	
LSD $_{I*D}$		0.0032			LSD $_{I}$	0.0026
D						
Distances between sub-lines (D)		40	60	80		
Average distances		0.0398	0.0566	0.0725		
LSD $_{D}$		0.0017				

CONCLUSION

It can be concluded that the monocrystalline solar panel with the drip irrigation system at a distance of 40 cm achieved the best results in irrigation system efficiency (%), total seed yield (kg/ha), with the lowest operating costs ($/kWh).

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