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Applying smart irrigation system to rationalize water consumption for alfalfa crop under Al-Farafra Oasis conditions

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ABSTRACT

Given the limited water resources, maximizing water productivity and feed quality in arid and semi-arid environments, particularly in sandy soils with low water-holding capacity, is a significant challenge for maintaining livestock productivity. A study was conducted for two successive winter seasons (2022/2023 and 2023/2024) in the Al-Farafra Oasis, New Valley Governorate, Egypt, to evaluate the impacts of irrigation techniques (IT) and soil amendment rates (AR) on the performance of winter alfalfa (*Medicago sativa L.*). This study compares two irrigation management strategies, smart irrigation technique (SIT) and manual irrigation technique (MIT), under two irrigation systems: sprinkler irrigation (SI) and leaky pipe irrigation (LPI). Four soil amendment rates were used: T1 (0 t fed^{-1}clay, 0 kg fed^{-1} humic acid, 0 t fed^{-1} biochar), T2 (5 t fed^{-1}, 10 kg fed^{-1}, 3 t fed^{-1}), T3 (10 t fed^{-1}, 20 kg fed^{-1}, 6 t fed^{-1}), and T4 (15 t fed^{-1}, 30 kg fed^{-1}, 9 t fed^{-1}). The combination of SIT, LPI, and highest AR T4 was significantly greater in forage quality, marketable yield (MY), water use efficiency (WUE), and irrigation water use efficiency (IWUE) than all other treatments. The highest values of MY were (22.96 and 23.11 t ha^{-1}), WUE (3.04 and 3.09 kg m^{-3}), and IWUE (2.75 and 2.79 kg m^{-3}) were found during the first and second respective seasons at SIT and T4 under LPI treatment. In contrast, the lowest performance was recorded at MIT and T1 under SI treatment. The water consumption (WC) and irrigation water application (IR) were also reduced by up to 30 and 20%, respectively, under the best treatment. In conclusion, the combination of smart irrigation practices, efficient ways to deliver water, and amending soils in a purposefully efficacious manner is a sustainable method to improve water productivity, mitigate water losses, and improve alfalfa forage quality. Treatment T3 provided similar results to T4 at lower costs and with fewer amendment inputs. This work demonstrates a useful method to optimize water usage in agricultural practices, including in arid parts of the world like Egypt, to sustain agriculture, support farmers, and improve food security in the future.

1. Introduction

Alfalfa (*Medicago sativa L.*) is one of the main forage crops in Egypt due to its high nutritional quality and adaptability to a wide range of agro-climatic conditions. It plays a critical role in the livestock sector by providing high-protein feed for dairy cattle, sheep, goats, and other ruminants (Abdel-Gawad et al., 2020; Feedipedia, 2021). However, alfalfa also has high water requirements, especially in arid and semi-arid regions such as Egypt. In such water-stressed environments, excessive irrigation of alfalfa may become unsustainable due to limited water availability and increasing competition for water resources (Abdel-Motagally et al., 2022; Khalifa and El-Hadidi, 2023). Given the importance of water for agriculture in Egypt, optimizing irrigation practices and improving soil water management are essential. Recent advances in smart irrigation systems and soil amendments such as biochar, bentonite clay, and humic

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acid have demonstrated great potential to enhance water use efficiency (WUE) without compromising yield or quality (Mahmoud et al., 2021; Mohamed et al., 2023a). Smart irrigation systems help reduces drought stress by maintaining chlorophyll content and favorable root-to-shoot ratios in alfalfa under water-limited conditions (Fahad et al., 2020). These systems also minimize over-irrigation, nutrient leaching, and soil degradation (El-kholy and El-Helaly 2021), and have been shown to significantly improve irrigation efficiency and crop productivity under arid conditions in Egypt (Abdel-Aziz, 2016; Ali, 2024). Sensor-based drip irrigation systems have reduced water use by 25–30% while achieving higher yields than conventional methods (Mohamed et al., 2023b). In semi-arid climates, soil moisture sensors improved dry matter yield by 18.5% (Ammar et al., 2024). Incorporating machine learning into smart irrigation controllers further enhanced irrigation scheduling and biomass yield by 20% (Zhang et al., 2024). Similarly, drip irrigation improved water productivity by 28% while maintaining yields equivalent to conventional systems (Zhang et al., 2019). Leaky pipe irrigation systems have consistently outperformed sprinkler systems by reducing water loss and improving WUE by 25–35%, mainly due to improved moisture retention in the root zone (Liu & Zhang, 2020; Yang et al., 2021; El-Morshedy et al., 2023). Soil amendments such as biochar and bentonite clay have shown the ability to improve soil water-holding capacity, nutrient availability, and crop performance under drought stress (Hossain et al., 2019; Razzaghi & Richards, 2020; Li et al., 2021). These amendments have also improved soil properties and WUE across different irrigation systems (Wu et al., 2019; Bishara et al., 2020; Zhang et al., 2020). Saja and Abbas (2023, 2024) demonstrated that these materials increased nutrient availability in desert soils and supported the growth of crops like alfalfa. Furthermore, they help suppress soil acidity, enhance soil health, and reduce nitrogen losses in saline conditions, which contribute to improving WUE (Brtnicky et al., 2021; Sila Abdeen, 2020). When combined with deficit irrigation or smart scheduling, these amendments can reduce irrigation water use by up to 30% without yield penalties (Ahmed et al., 2022; Yang et al., 2023). Humic acid, when applied under 80% of ETc, produced yields similar to full irrigation while significantly improving IWUE (Abdelhafez et al., 2021). Biochar has also been shown to enhance soil structure and reduce actual evapotranspiration (ETa) by improving moisture retention and root development (Cao et al., 2023). Although limited studies have investigated bentonite clay alone in alfalfa, its combination with biochar and humic substances has proven synergistic in enhancing soil water-holding capacity and WUE (Nasr et al., 2022; El-Morshedy et al., 2023). While sprinkler systems provide moderate improvements in uniform water distribution, leaky pipe systems have demonstrated superior performance in reducing ETa and enhancing IWUE by minimizing surface evaporation and delivering water more effectively (Golabi & Akhoonali, 2003; Ali, 2023). Smart irrigation technologies incorporating Internet of Things (IoT) platforms offer real-time monitoring and dynamic irrigation scheduling, further enhancing precision irrigation and crop performance under variable environmental conditions (Ahmadi Pargo et al., 2025). As the demand for more sustainable water management in Egyptian agriculture continues to grow, especially for water-intensive crops like alfalfa, there is a pressing need to investigate the combined effects of smart irrigation practices and soil amendments to enhance productivity while conserving water. This study contributes to the growing body of research on integrated water-saving practices in forage crop production under arid and semi-arid conditions.

Therefore, this study aims to evaluate the impacts of smart irrigation techniques compared to manual irrigation techniques, combined with soil amendments (clay, humic acid, and biochar) under two irrigation methods (sprinkler and leaky pipe), in terms of alfalfa yield, forage quality, water consumption (WC), water use efficiency (WUE), and irrigation water use efficiency (IWUE) under arid and semi-arid conditions.

2. Materials and methods

2.1. Experiment

Field experiments were conducted in the Al-Farafra Oasis, New Valley Governorate, Egypt (26°54′31″N, 27°54′19″E; 90 m above sea level) during two successive winter seasons (2022/2023 and 2023/2024). A split-split plot design with three replicates was used. The experimental area was divided into 45 m² plots, each bordered by a 3 m wide barren strip to prevent horizontal water infiltration. Statistical analysis was performed using CoStat software following the procedures of Snedecor and Cochran (1989). Winter alfalfa (*Medicago sativa L., cv.*) Sakha1 was irrigated using two techniques: the smart irrigation technique (SIT), implemented via an INKBIRD IIC-800-WIFI controller capable of managing eight zones with real-time scheduling, weather-responsive adjustments, and soil moisture sensing; and the manual irrigation technique (MIT), which received full irrigation equivalent to 100% of crop evapotranspiration (ETc), as calculated by FAO guidelines. Both techniques were evaluated under four soil amendment rates (AR), comprising clay, humic acid, and biochar as follows: T1 (0 t fed^{-1}, 0 kg fed^{-1}, 0 t fed^{-1}), T2 (5 t fed^{-1}, 10 kg fed^{-1}, 3 t fed^{-1}), T3 (10 t fed^{-1}, 20 kg fed^{-1}, 6 t fed^{-1}), and T4 (15 t fed^{-1}, 30 kg fed^{-1}, 9 t fed^{-1}). All treatments were applied under two different irrigation systems: sprinkler irrigation (SI) and leaky pipe irrigation (LPI). Alfalfa performance was evaluated through multiple agronomic and quality indicators, including dry matter content (DMC, %), regrowth rate (RR, %), ash content (AC, %), crude fiber (CF, %), crude protein (CP, %), chlorophyll content (CC, %), and marketable yield (MY, t ha^{-1}). Seasonal actual evapotranspiration (ETa, mm), water use efficiency (WUE, kg m^{-3}), and irrigation water use efficiency (IWUE, kg m^{-3}) were also determined across the different combinations of irrigation methods and soil amendment rates.

2.2. Soil characteristics

The samples collected were analyzed for the physical and chemical properties of the soil. In Tables 1 and 2, the progress of the procedure was taken from the method described by Page et al., (1982); Klute, (1986).

2.3. Quality of irrigation water

Table 3 shows the results of chemical analyses of the irrigation water, which was carried out using the procedures outlined by Ayers and Westcot (1994).

Table 1

Physical characteristics of the experimental soil.

Soil depth cm	Particle size distribution %					Textural class	OM %	ρ_b g cm^{-3}	Ks cm h^{-1}	FC %	WP %	AW %
	C. sand	M. sand	F. sand	Silt	Clay							
0-20	71.12	11.41	5.68	4.53	7.26	L.S.	0.31	1.58	11.46	15.82	5.84	9.98
20-40	70.26	10.34	4.12	5.71	9.57	L.S.	0.23	1.56	10.34	16.69	5.97	10.72
40-60	68.64	9.52	3.71	6.30	11.83	L.S.	0.18	1.53	8.91	18.95	6.11	12.84

C=coarse; M=medium; F=fine

Table 2

Chemical characteristics of the experimental soil.

Soil depth cm	EC dS m^{-1}	pH	$CaCO_3$ %	CEC cmole kg^{-1}	Soluble ions (meq/l) in saturated soil paste extract							
					Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	CO_3^{--}	SO_4^{--}
0-20	7.76	8.19	12.43	9.65	34.34	8.56	21.41	13.29	45.87	2.42	-	29.31
20-40	6.43	7.87	11.29	11.91	28.52	7.28	18.34	10.16	38.62	2.25	-	23.43
40-60	5.91	7.65	9.87	13.03	26.83	6.34	16.52	9.41	35.15	2.13	-	21.82

Table 3

Chemical analysis of irrigation water.

Sample	pH	EC dS m^{-1}	SAR	Soluble cations, meq/l				Soluble anions, meq/l			
				Na^+	K^+	Ca^{++}	Mg^{++}	CL^-	HCO_3^-	$CO_3^=$	$SO_4^=$
Mean	7.82	3.57	5.23	15.93	1.24	11.45	7.08	18.73	15.51	-	1.46

2.4. Mineral fertilizer rates

All experimental plots were fertilized according to the recommended rates established by the Egyptian Ministry of Agriculture. The fertilizers were applied as follows:

- Nitrogen (N): Supplied as ammonium sulfate [$(NH_4)_2SO_4$] at a total rate of 200 kg fed^{-1} throughout the growing season. 50 kg fed^{-1} was applied with the first irrigation after planting, followed by 25 kg fed^{-1} injected into the irrigation system after each alfalfa cutting.
- Phosphorus (P): Supplied as calcium superphosphate (15.5% P_2O_5) at a total seasonal rate of 250 kg fed^{-1}. An initial dose of 50 kg fed^{-1} was applied before planting, followed by 25 kg fed^{-1} after each harvest to support root development and regrowth.
- Potassium (K): Supplied as potassium sulfate (K_2O) at a total rate of 150 kg fed^{-1}. An initial dose of 50 kg fed^{-1} was applied before planting, and the remaining amount was split, with 50% applied after the first or second mowing to enhance regrowth and improve forage quality.

2.5. Reference evapotranspiration

The daily Agro meteorological data for the region of Farafra spanning the years 2022 and 2023 were gathered from NASA's POWER (Prediction of Worldwide Energy Resources) database. The Penman-Monteith equation (FAO-56 method) was utilized, ETo was calculated, and the average of the two seasons was taken. as shown in Table 4 (Allen et al., 1998).

Table 4

Calculated reference evapotranspiration (mm day^{-1}) through winter alfalfa crop growth period.

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ET_o (mm day^{-1})	6.83	4.98	4.21	4.34	4.91	6.46	7.79	8.02	9.45	9.17	8.29	7.96

2.6. Crop evapotranspiration

The crop evapotranspiration ETc calculated using the following equation (Allen et al., 1998) is displayed in Table 5:

$$ETc = K_{c\,FAO} \times ET_o \quad \text{... [1]}$$

where:

ETc : Crop evapotranspiration (mm day^{-1}),
Kc_{FAO} : Crop coefficient, and
ETo : Reference evapotranspiration (mm day^{-1}).

Table 5

Calculated crop evapotranspiration (ETc) in mm for five consecutive alfalfa cuttings during the crop growth period.

Cut No.	Stages	Initial	Develop.	Mid	Late	Seasonal
	Kc_{FAO} (-)	0.30	0.75	1.15	0.85	--------
	Eff. Rainfall (mm)	0	0	0	0	0
First	Planting date	3/10 to 17/10	18/10 to 6/11	7/11 to 1/12	8/11 to 6/12	3/10 to 6/12
	Period length (day)	15	20	25	5	65
	ETo (mm)	102.45	125.50	123.73	21.05	372.73
	$ETc_{100\%}$ (mm)	30.74	94.13	142.29	17.89	285.05
Second	Planting date	7/12 to 11/12	12/12 to 18/12	19/12 to 31/12	1/1 to 5/1	7/12 to 5/1
	Period length (day)	5	7	13	5	30
	ETo (mm)	21.05	29.47	54.73	21.70	126.95
	$ETc_{100\%}$ (mm)	6.32	22.10	62.94	18.45	109.81
Third	Planting date	6/1 to 10/1	11/1 to 17/1	18/1 to 1/2	2/1 to 6/2	6/1 to 6/2
	Period length (day)	5	7	15	5	32
	ETo (mm)	21.70	30.38	65.67	24.55	142.30
	$ETc_{100\%}$ (mm)	6.51	22.79	75.52	20.87	125.69
Fourth	Planting date	7/2 to 11/2	12/2 to 19/2	20/2 to 8/3	9/3 to 13/3	7/2 to 13/3
	Period length (day)	5	8	17	5	35
	ETo (mm)	24.55	39.28	95.87	32.30	192.00
	$ETc_{100\%}$ (mm)	7.37	29.46	110.25	27.46	174.54
Fifth	Planting date	14/3 to 18/3	19/3 to 27/3	28/3 to 14/4	15/4 to 19/4	14/3 to 19/4
	Period length (day)	5	9	18	5	37
	ETo (mm)	32.30	58.14	134.90	38.95	264.29
	$ETc_{100\%}$ (mm)	9.69	43.61	155.14	33.11	241.55

2.7. Applied irrigation water IR

The indicated amounts of applied irrigation water (IR) for the winter alfalfa crop could be found by using the following equation (Keller and Karmeli, 1974):

$$IR_{100\,\%} = (ETc - pe)(Kr/Ea) + LR \quad \text{... [2]}$$

where:

$IR_{100\,\%}$: Seasonal applied irrigation water (mm $period^{-1}$),
ETc : Crop evapotranspiration (mm $period^{-1}$),
Pe: Effective rainfall (mm $season^{-1}$), Table 5,
Kr: Correction factor for limited wetting at alfalfa present round coverage by canopy 80%, Kr = 0.90. (Smith 1992),
Ea: Irrigation efficiency for leaky pipe = 90 % and sprinkler = 75 % (Allen et al., 1998), and
LR: Leaching requirements, (0.12 × ETc), mm.

2.8. Water consumption

The actual consumptive water (WC) was determined using the following equation as described by Doorenbos and Pruitt (1984).

$$WC = \frac{M_2 - M_1}{100} \times d_b \times D \quad \text{... [3]}$$

where:

WC: Actual water consumption (mm),

M_1 and M_2: Moisture content before and after irrigation respectively (%),

d_b: Soil specific density, and

D: Mean depth (mm).

2.9. *Water use efficiency (WUE) and irrigation water use efficiency (IWUE)*

WUE and IWUE were determined by the equations [4] and [5] (Howell et al., 2001, Michael, 1978):

$$\text{WUE} = \frac{\text{MY}}{\text{WC}} \quad \text{... [4]}$$

$$\text{IWUE} = \frac{\text{MY}}{\text{IR}} \quad \text{... [5]}$$

where:

WUE and IWUE: Water use efficiency and irrigation water use efficiency (kg m^{-3}), and

MY: Marketable yield of alfalfa (kg ha^{-1}).

IR: Seasonal applied irrigation water, (m^3), Table 6.

Table 6

Presents the calculated applied irrigation water (IR) for five consecutive alfalfa cuttings during the crop growth period using manual irrigation technique (MIT).

IS	Cut No.	Applied irrigation water, mm ($IR_{100\%}$)				
		Growth stages				
		Initial	Develop.	Mid	Late	Seasonal
SI	First	40.55	124.18	187.72	23.61	376.05
	Second	8.33	29.16	83.03	24.33	144.86
	Third	8.59	30.06	99.63	27.53	165.81
	Fourth	9.72	38.87	145.45	36.22	230.25
	Fifth	12.78	57.53	204.67	43.68	318.66
LPI	First	34.40	105.35	159.26	20.03	319.04
	Second	7.07	24.74	70.45	20.65	122.90
	Third	7.29	25.50	84.53	23.36	140.67
	Fourth	8.24	32.97	123.40	30.73	195.35
	Fifth	10.85	48.81	173.64	37.06	270.35

3. Results and discussions

3.1. *Effect of IT and AR on quality parameters for alfalfa crop under SI and LPI irrigation systems*

Data presented in Table 7 show that the smart irrigation technology (SIT) using the highest rate of sand soil amendments made up of T4 in combination with leaky pipe irrigation (LPI), had the highest values for many of the quality traits of winter alfalfa dry matter content (DMC), regrowth rate (RR), ash content (AC), crude protein (CP), and chlorophyll content (CC), with the results being 18.23%, 61.92%, 10.35%, 23.76%, and 2.47% in the first season, and 18.59%, 63.09%, 10.59%, 24.23%, and 2.54% in the second season, respectively. Similarly, crude fiber (CF) had the lowest value, with 21.16% and 20.73% in the two seasons. The manual irrigation technique (MIT) with no sand soil amendments T1 under sprinkler irrigation (SI), had the lowest values for DMC, RR, AC, CP, and CC, with the values being 11.85%, 39.27%, 7.45%, 16.25%, and 1.35%, in the first season, and 12.08%, 40.02%, 7.61%, 16.57%, and 1.39% in the second season, respectively (Table 8). CF had the highest values under this treatment, with 26.68% and 26.13%, respectively. These findings indicate that the patterns observed were replicated in both seasons. The observed results could happen for several reasons. The SIT technique allowed for accurate water application to the crop responsive to weather and soil moisture, minimizing moisture stress and encouraging overall physiological functions such as protein production and increased chlorophyll production. LPI system provided adequate low-loss irrigation by slowly and directly applying water to crop roots, contrasting with a sprinkler irrigation system. Also, SI system delivery systems are typically associated with higher surface evaporation and runoff. The combination of clay, humic acid, and biochar enhanced sandy soil's ability to hold water, provide nutrient availability, and support activity from microbial organisms. Clay limited percolation, humic acid improved nutrient intake and stimulated root development, and biochar improved soil structure and allowed for long-term soil fertility improvement. The combination of additions created the finest overall soil-plant environment, leading to improved forage quality and a relatively higher allocation of all resources. These results were consistent with previous studies conducted by Bishara et al. (2020); Ahmed et al. (2022); Mahmoud et al. (2021); Nasr et al. (2022); El-Morshedy et al. (2023), which demonstrated the beneficial impacts of smart irrigation, leaky pipe irrigation system and soil amendments for alfalfa productivity and quality under arid conditions.

Table 7

Effect of IT and AR on DMC, RR and AC of alfalfa crop under SI and LPI irrigation systems for seasons 2022/2023 and 2023/2024.

IT	IS	AR (t fed-1)	DMC (%)		RR (%)		AC (%)	
			1st	2nd	1st	2nd	1st	2nd
MIT	SI	T1	11.85n	12.08n	39.27p	40.02p	7.45o	7.61o
		T2	13.31l	13.56l	44.43m	45.25m	7.98m	8.15m
		T3	14.83i	15.11i	49.75i	50.69i	8.41j	8.59j
		T4	16.47e	16.79e	54.13e	55.17e	8.93g	9.12g
	LPI	T1	12.32m	12.55m	41.81o	42.62o	7.89n	8.07n
		T2	13.76k	14.03k	46.35k	47.23k	8.27l	8.46l
		T3	15.29h	15.57h	51.13h	52.11h	8.85h	9.05h
		T4	16.53d	16.85d	56.57c	57.69c	9.18f	9.39f
SIT	SI	T1	13.35l	13.61l	44.29n	45.15n	8.32k	8.51k
		T2	14.68j	14.96j	49.45j	50.37j	8.87h	9.06h
		T3	16.32f	16.64f	54.07f	55.09f	9.41d	9.61d
		T4	17.81b	18.16b	59.32b	60.46b	9.93b	10.15b
	LPI	T1	13.79k	14.05k	46.18l	47.04l	8.68i	8.87i
		T2	15.47g	15.76g	51.52g	52.53g	9.25e	9.46e
		T3	17.64c	17.97c	56.35d	57.46d	9.76c	9.98c
		T4	18.23a	18.59a	61.92a	63.09a	10.35a	10.59a

T1= (0 t fed-1, 0 kg fed-1, 0 t fed-1), T2= (5 t fed-1, 10 kg fed-1, 3 t fed-1), T3= (10 t fed-1, 20 kg fed-1, 6 t fed-1) and T4= (15 t fed-1, 30 kg fed-1, 9 t fed-1)

Table 8

Effect of IT and AR on CF, CP and CC of alfalfa crop under SI and LPI irrigation systems for seasons 2022/2023 and 2023/2024.

IT	IS	AR (t fed-1)	CF (%)		CP (%)		CC (%)	
			1st	2nd	1st	2nd	1st	2nd
MIT	SI	T1	26.68a	26.13a	16.25o	16.57o	1.35o	1.39o
		T2	25.59c	25.06c	17.38n	17.71n	1.47n	1.51n
		T3	24.17f	23.68f	18.73k	19.09k	1.72j	1.77j
		T4	23.32i	22.84i	20.91f	21.32f	1.78h	1.83h
	LPI	T1	24.26e	23.77e	17.69m	18.03m	1.52m	1.56m
		T2	23.73g	23.24g	18.45l	18.81l	1.64k	1.68k
		T3	22.59k	22.12k	19.87h	20.25h	1.93f	1.98f
		T4	22.41l	21.95l	21.52d	21.94d	2.05d	2.11d
SIT	SI	T1	25.73b	25.21b	18.76k	19.12k	1.61l	1.65l
		T2	24.65d	24.14d	19.39j	19.77j	1.75i	1.80i
		T3	23.41h	22.93h	20.61g	21.01g	2.06d	2.12d
		T4	22.28m	21.83m	21.94c	22.36c	2.12c	2.18c
	LPI	T1	23.34i	22.86i	19.52i	19.89i	1.81g	1.86g
		T2	22.72j	22.25j	21.37e	21.78e	1.96e	2.01e
		T3	21.29n	20.85n	23.69b	24.15b	2.34b	2.40b
		T4	21.16o	20.73o	23.76a	24.23a	2.47a	2.54a

T1= (0 t fed-1, 0 kg fed-1, 0 t fed-1), T2= (5 t fed-1, 10 kg fed-1, 3 t fed-1), T3= (10 t fed-1, 20 kg fed-1, 6 t fed-1), and T4= (15 t fed-1, 30 kg fed-1, 9 t fed-1)

3.2. Effect of IT and AR on applied irrigation water (IR) for alfalfa crop under SI and LPI irrigation systems

Table 9 data indicate that both the added irrigation water techniques and the soil amendment rate (AR) explicitly affected the amount of total seasonal irrigation water applied (IR) during alfalfa production. As compared to the manual irrigation technique (MIT) with the sprinkler irrigation (SI), the smart irrigation technique (SIT), and especially in combination with the individually operating leaky pipe irrigation system (LPI), applied less irrigation water in all soil amendment treatments. The most efficient treatment, SIT with LPI at the highest soil amendment rate T4, recorded applied irrigation amounts of 833.91 mm during the first season and 829.74 mm during the second season. In contrast, the least efficient treatment, MIT with SI at the lowest amendment rate T1, recorded 1039.81 and 1034.93 mm, respectively, which equated to a reduction of 19.80% and 19.83%, respectively, in the first and second seasons when compared to the lowest mean gardening treatment T1(control treatment). This significant reduction highlights the potential for water savings when combining precision irrigation and soil amendments. The irrigation water reduction was primarily attributed to three interrelated conditions. First, the SIT operated off continuous real-time soil moisture and climate data, allowing the system to prevent over-irrigation and irrigate only as needed. Secondly, the LPI system increased water application efficiency through slow and targeted delivery to minimize surface runoff and evaporation. Thirdly, soil amendments used in this study, such as clay, humic acid, and biochar, significantly improve soil structure. Clay reduced infiltration loss, humic acid increased nutrient and water holding capacity, and biochar increased porosity and microbial activity to increase water capacity and ability to store and supply water to crops. This aligns with findings from El-Morshedy et al. (2023); Liu and Zhang (2020) that confirmed the water reduction potential from LPI systems in place of sprinklers. In addition, it is consistent with Bishara et al. (2020); Hossain et al. (2019), who illustrated the beneficial impact of organic soil amendments, especially clay and biochar, to improve water holding capacity and decrease water requirement for irrigation in hot arid zones. Coupling innovative irrigation technology with an efficient irrigation delivery system augmented with organic soil amendments provides a sustainable approach to enhance water productivity in Egyptian desert forage production systems.

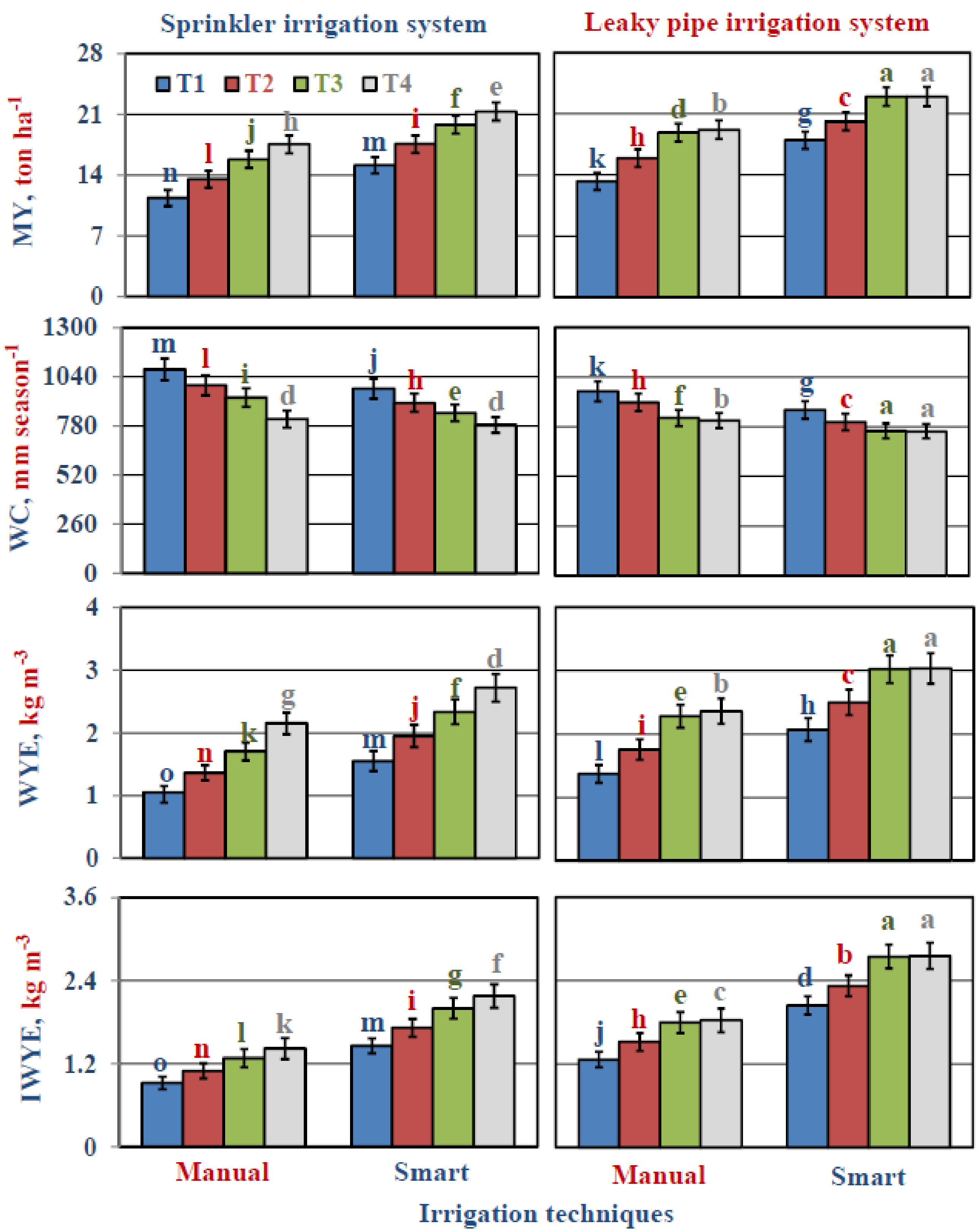
Table 9

Effect of IT and AR on seasonal applied irrigation water (IR) for alfalfa crop using smart irrigation technology (SIT) during seasons 2021/2022 and 2022/2023.

IS	AR, (t fed^{-1})	Seasonal applied Irrigation water, (mm)	
		1st	2nd
SI	T1	1039.81	1034.93
	T2	1023.59	1017.72
	T3	991.37	986.43
	T4	979.65	976.58
LPI	T1	879.53	875.36
	T2	865.76	862.91
	T3	835.48	831.26
	T4	833.91	829.74

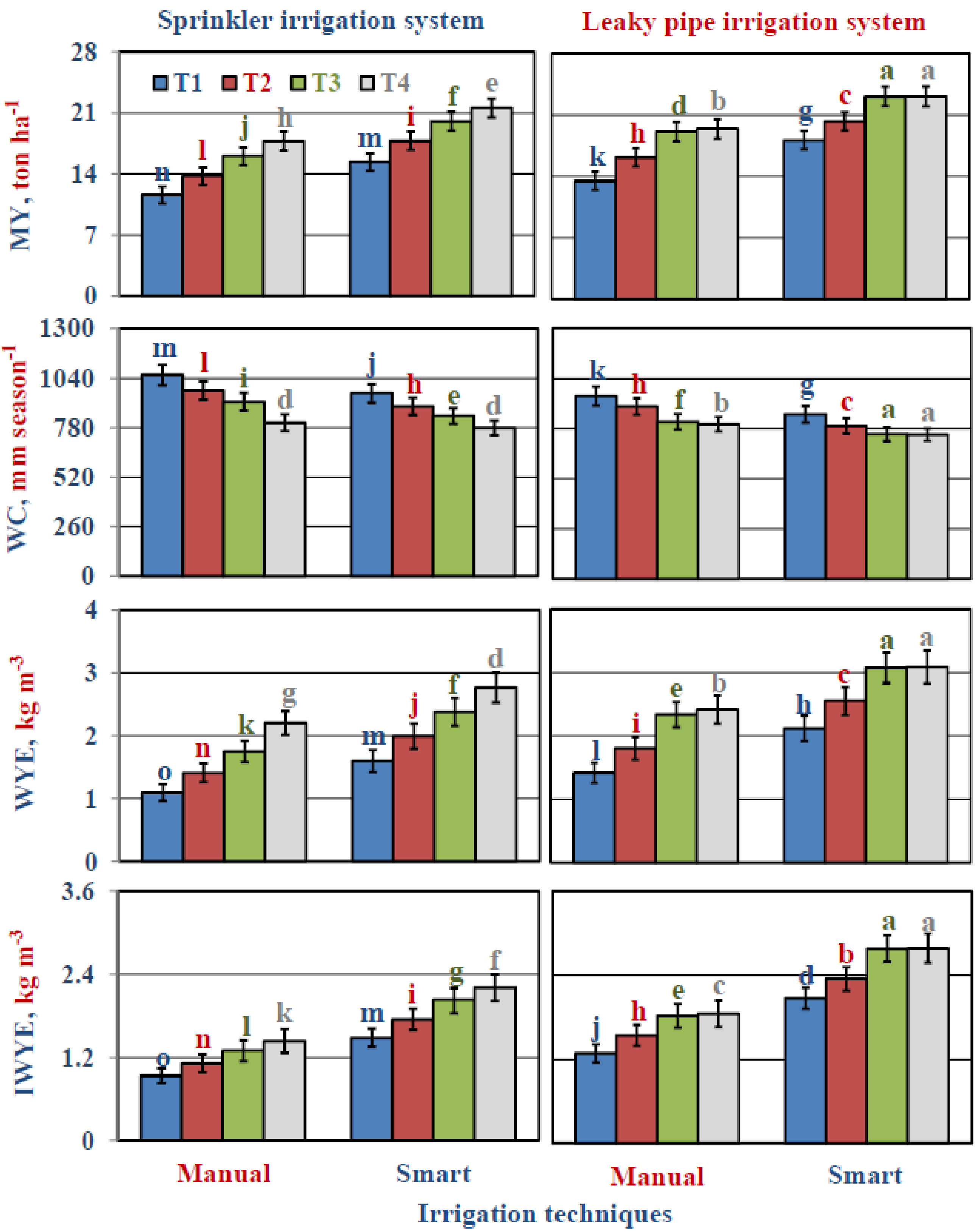
3.3. Effect of IT and AR on MY for alfalfa crop under SI and LPI irrigation systems

Data in Figs. 1 and 2 show a clear general trend, showing that the smart irrigation technique (SIT) always had higher alfalfa yield than the manual irrigation technique (MIT) for each sandy soil amendment level. This improvement was particularly noted at higher amendment rates, as SIT substantially improved the marketable yield (MY) across both seasons. The same ability to increase MY was also present in the leaky pipe irrigation (LPI) system compared to the sprinkler irrigation (SI) system for all treatment combinations. Again, the (LPI) irrigation system's improved ability to convey water locally and with less water loss greatly benefits agricultural production in arid environments. Another significant trend observed from the data was the positive relationship between greater amendment rates and increased marketable yield. To put it another way, the SIT was more beneficial for yield even while using lower amounts of clay, humic acid, and biochar inputs. Under both irrigation systems, productivity improvement was evident; however, the effect was more pronounced when using the SI system, as it has a reduced soil moisture retention capacity, which increased the need for soil amendment inputs. The SIT, combined with the highest amendment rate T4, under the LPI system, produced the greatest MY for winter alfalfa at 22.96 and 23.11 t ha^{-1} for both seasons.



T1= (0 t fed-1, 0 kg fed-1, 0 t fed-1), T2= (5 t fed-1, 10 kg fed-1, 3 t fed-1), T3= (10 t fed-1, 20 kg fed-1, 6 t fed-1), and T4= (15 t fed-1, 30 kg fed-1, 9 t fed-1)

Fig. 1. Effect of irrigation techniques and soil amendment rates on marketable yield (MY), water consumption (WC), water use efficiency (WUE), and irrigation water use efficiency (IWUE) of alfalfa under sprinkler and leaky pipe irrigation systems during the 2022 and 2023 seasons.



T1= (0 t fed-1, 0 kg fed-1, 0 t fed-1), T2= (5 t fed-1, 10 kg fed-1, 3 t fed-1), T3= (10 t fed-1, 20 kg fed-1, 6 t fed-1), and T4= (15 t fed-1, 30 kg fed-1, 9 t fed-1)

Fig. 2. Effect of irrigation techniques and soil amendment rates on marketable yield (MY), water consumption (WC), water use efficiency (WUE), and irrigation water use efficiency (IWUE) of alfalfa under sprinkler and leaky pipe irrigation systems during the 2023 and 2024 seasons.

In contrast, the lowest MY was produced at the MIT with no soil amendment T1 under SI system, with 11.35 and 11.58 t ha^{-1} (for both seasons), respectively. The MY percentage increase from the best treatment (SIT and T4 under LPI) to the worst treatment (MIT and T1 under SI) was 102.29% and 99.57% for both seasons, respectively, indicating almost doubled MY. The results are based on combining higher precision irrigation technologies and improved soil conditions. SIT promotes less over-irrigation because of real-time information on field conditions and weather. LPI delivers water to the root zone using low-loss targeted methods. The improved nutrients retained within sandy soils and the soil amendments' hydro-holding capacity led to greater root growth and crop productivity. These results are in agreement with Bishara et al. (2020); Mahmoud et al. (2021); Ahmed et al. (2022); El-Morshedy et al. (2023), who discussed improved forage yield and efficiency with smart irrigation and technology for optimum irrigation and use of organic soil amendments in arid environments.

3.4. Effect of IT and AR on WC for alfalfa crop under SI and LPI irrigation systems

Data in Figs. 1 and 2 reveal a clear and consistent pattern in which the irrigation water application techniques (IT) had a direct impact on the actual water consumption (WC) values observed while winter alfalfa was grown, irrespective of different amounts of sandy soil amendment rates (AR). These figures illustrate that the smart irrigation technique (SIT) had lower WC values under all amendment treatments than the manual irrigation technique (MIT). This was most pronounced for the higher level of soil amendment, revealing that the combination of precision irrigation scheduling and soil-enhancement input dramatically reduced water losses during each growing season.

Like SIT, the leaky pipe irrigation (LPI) system also resulted in lower WC values than the sprinkler irrigation system (SI), regardless of the level of amendment rate applied. When working with sandy soil, which tends to have relatively high evaporation rates and generally low moisture-holding capacity, it is better to use the LPI system than the SI system. The LPI system applied water more slowly and directly to the effective root zone, reduced evaporation and runoff effects, and therefore improved water use. The data consistently demonstrated an inverse relationship between soil amendment rate and WC values, as we increased the rates of clay, humic acid, and biochar, we noted a decrease in WC under both the SI and LPI invasive techniques. The effect was more pronounced under SI compared to LPI because surface water losses are higher with sprinkler irrigation due to evaporation and runoff, and soils without amendments have low to no water-holding capacity. LPI is a more localized and slower application of water, which reduces surface water loss and improves the use of irrigation water. The minimum WC was achieved with the SIT technique with the highest sand soil amendment level T4 with under LPI system at 755.87 and 748.63 mm $season^{-1}$ in the first and second seasons, respectively. The opposite highest WC were achieved under MIT without sand soil amendments, T1 with under SI system at 1078.49 and 1057.14 mm $season^{-1}$ in the first and second seasons, respectively, a reduction of 29.91 and 29.18% WC under the most efficient treatment to least efficient treatment (control). The difference in WC is mainly attributed to the responsiveness of SIT compared to MIT, with SIT for irrigation management based on immediate soil moisture and environmental conditions, preventing over-irrigation. Furthermore, with LPI system, soil water placement allowing for water and nutrient uptake, and the addition of soil amendments was key for improving soil moisture dynamics, as clay reduced water and soil potential losses through percolation, humic acid improved the nutrient uptake and root activity, and biochar improved soil porosity and microbial functions. In summary, all the amendments increased the soil's water-holding capacity and reduced deep percolation, providing more water to the plants, especially in arid regions conditions. These findings were congruent with reported results by Hossain et al. (2019); Razzaghi and Richards (2020); Mahmoud et al. (2021); El-Kholy and El-Helaly (2021); Cao et al. (2023) who reported the benefits of using both precision irrigation systems and organic soil amendments to reduce evapotranspiration and maximize water productivity in arid and semi-arid regions forage production systems.

3.5. Effect of IT and AR on WUE and IWUE for alfalfa crop under SI and LPI irrigation systems

The data analyzed in Figs. 1 and 2 suggest positive impacts of some added irrigation water techniques (IT) and soil amendment rates (AR) on winter alfalfa water use efficiency (WUE) and irrigation water use efficiency (IWUE). The data showed a clear trend that when the Smart Irrigation Technique (SIT) was compared to the manual irrigation technique (MIT), there were increased values for both efficiency measurements in every treatment level. The most significant improvement was recorded when combining the SIT with the leaky pipe irrigation (LPI) systems, and the highest soil amendment T4. This application produced the maximum WUE and IWUE, producing 3.04 and 2.75 kg m^{-3} in the first season, and 3.09 and 2.79 kg m^{-3} in the second season, respectively. The minimum WUE and IWUE recorded was for MIT with sprinkler irrigation (SI) with no soil amendments T1, and both measurements then declining to only 1.05 and 0.92 kg m^{-3} over the first season, and 1.10 and 0.94 kg m^{-3} over the second. Therefore, this treatment showed relative WUE of 189.52 and 180.91%, and IWUE increases of 198.91 and 196.81% in the first and second seasons, respectively, in the most efficient treatment versus the least efficient treatment (control). Three combined factors facilitate this increase. The first is that SIT enables precise irrigation scheduling based on accurate weather and soil moisture conditions. Consequently, SIT minimized the likelihood of over-irrigation. Next, LPI delivered water locally, directly at the effective root zone, and reduced water loss to evaporation and deep percolation caused by traditional irrigation methods. Lastly, soil amendments, such as clay, humic acid, and biochar, improved the physical and biological capacity of sandy soil. Sandy soil washed away more quickly due to rainfall and irrigation. Improvements to sandy soil resulted in enhanced water retention, increased nutrient uptake, and increased microbial activity. These preparations improved the soil-water-plant relationship and cumulatively enhanced crop water productivity. The results were very much in line with what Abdelhafez et al. (2021); Mahmoud et al. (2021); Nasr et al. (2022); El-Morshedy et al. (2023) found about using smart irrigation technique and soil amendments under drip irrigation systems to produce improvements to WUE and IWUE in arid and semi-arid conditions. Our results are also supported by Razzaghi and Richards (2020); Bishara et al. (2020); Ali (2023), whose findings suggest that soil conditioners improved soil water function and efficiency for sandy soils. Collectively. SIT, LPI, and targeted soil amendments can provide an ideal and scalable solution for increasing water productivity in desert forage crop production systems.

4. Conclusions

This study concluded that the combination of smart irrigation technique (SIT) with the leaky pipe (LPI) irrigation system and higher levels of soil amendments T4 (15 t fed^{-1}, 30 kg fed^{-1}, 9 t fed^{-1}) significantly enhanced winter alfalfa yield and quality parameters in the Al-Farafra Oasis, New Valley Governorate, Egypt. The optimal treatment improved all quality parameters except crude fiber (CF) and doubled marketable yield (MY). Water use efficiency (WUE) improved by 189% and 182%, and irrigation water use efficiency (IWUE) increased by 200% and 197% in the first and second experimental seasons, respectively. Finally, water use decreased by up to 30% from the control treatment (MIT with T1 under SI).

So, it is recommended to use the smart irrigation technique (SIT) under the LPI irrigation system, specifically treatment T3 (10 t fed^{-1}, 20 kg fed^{-1}, 6 t fed^{-1}), which produced similar results to treatment T4, as a more economical option for farmers. It reduces input costs for soil amendments while maintaining high quality and productivity for the alfalfa crop, as well as efficiently rationalizes water consumption. For farmers and decision-makers globally, and specifically in Egypt, the adoption of SIT and LPI with soil amendments recommends a sensible option for improving water use, increasing productivity, and developing sustainable agriculture. It is considered one of the adaptation strategies that reduce the negative impacts of climate change on the agricultural sector, which helps rationalize the actual water consumption of strategic crops.

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تطبيق نظام الري الذكي لترشيد استهلاك المياه لمحصول البرسيم تحت ظروف واحة الفرافرة

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الملخص العربي

في ظل محدودية مصادر المياه يعد تعظيم إنتاجية المياه وجودة العلف في البيئات الجافة وشبه الجافة، وخاصة في التربة الرملية ذات القدرة المنخفضة على الاحتفاظ بالمياه، تحديًا كبيرًا للحفاظ على إنتاجية الثروة الحيوانية. لذا، تم إجراء هذه التجربة خلال موسمين شتويين متتاليين٢٠٢٢/٢٠٢٣م و٢٠٢٣/٢٠٢٤م في مزرعة بواحة الفرافرة، محافظة الوادي الجديد، مصر. تم ري البرسيم الشتوي (*Medicago sativa L*) باستخدام استراتيجيتين لإدارة مياه الري (TI) : تقنية الري الذكي (SIT) ومقارنتها بالطريقة اليدوية التقليدية للر (MIT) مع أضافة اربع معاملات من محسنات التربة (AR) : T1 = (صفر طن / فدان طين، صفر كجم / فدان حمض هيوميك، صفر طن / فدان بيوشار) وT2 = (٥ طن / فدان طين، ١٠ كجم / فدان حمض هيوميك، ٣ طن / فدان بيوشار) وT3 = (١٠ طن / فدان طين، ٢٠ كجم / فدان حمض هيوميك، ٦ طن / فدان بيوشار) وT4 = (١٥ طن / فدان طين، ٣٠ كجم / فدان حمض هيوميك، ٩ طن / فدان بيوشار) وذلك تحت نظامي الري بالرش (SI) ونظام الري بأنابيب تسرب المياه (LPI). أظهرت النتائج أن الجمع بين تقنية الري الذكي (SIT) ونظام الري بأنابيب تسرب المياه (LPI) وأعلى معاملة لمحسنات التربة T4 كان له تأثيرا كبيرا على جودة العلف، والمحصول القابل للتسويق (MY) ، وكفاءة الاستهلاك المائي (WUE)، وكفاءة الاستهلاك الإروائي (IWUE) ، مقارنة ببقية المعاملات. سجلت أعلى قيم للمحصول القابل للتسويق (٢٢,٩٦ و٢٣,١١ طن/هكتار)، وكفاءة الاستهلاك المائي (٣,٠٤ و٣,٠٩ كجم/م^{٣})، وكفاءة الاستهلاك الإروائي (٢,٧٥ و٢,٧٩ كجم/م^{٣}) في الموسم الأول والثاني على التوالي عند استخدام تقنية الري الذكي (SIT) والمعاملة T4 تحت الري بأنابيب تسرب المياه (LPI) في المقابل، تم تسجيل أدنى أداء عند استخدام الطريقة اليدوية للري (MIT) والمعاملة T1 تحت نظام الري بالرش (SI). كما تم ترشيد استهلاك المياه الفعلية (WC) وكمية مياه الري المضافة (IR) بنسبة تصل إلى ٣٠ و٢٠٪ على التوالي تحت أفضل معاملة. في الختام، يُعد الجمع بين ممارسات الري الذكي، والطرق الفعّالة لتوزيع المياه وتحسين التربة بشكل دقيق وفعّال، نهجًا مستدامًا لتحسين إنتاجية المياه، وتقليل هدرها، وتحسين إنتاجية وجودة علف البرسيم. كما أظهرت المعاملة T3 نتائج مشابهة للمعاملة T4 بتكاليف أقل ومدخلات تحسين تربة أقل. يقدّم هذا العمل أسلوبًا فعّالًا لترشيد استخدام المياه في الممارسات الزراعية، بما في ذلك المناطق القاحلة مثل مصر، لضمان استدامة الزراعة، ودعم المزارعين، وتعزيز الأمن الغذائي في المستقبل.