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Effect of Humic Acid Application And Soil Moisture Depletion Levels on Water Consumption and Water Use Efficiency of Potato (*Solanum Tuberosum* L.) Under a Drip Irrigation System

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Abstract

A field experiment was conducted during the spring growing season of 2025 at the First Agricultural Research Station (Al-Bu'aitha), College of Agriculture, University of Anbar, located in Ramadi District, Anbar Province, Iraq (43°10′48″ E, 33°26′40″ N). The experiment was carried out on a **sandy clay loam** soil classified as **Typic Torrifluvents**. The study aimed to evaluate the effect of humic acid application levels and soil moisture depletion percentages on crop water consumption and water use efficiency of potato (*Solanum tuberosum* L.) under a drip irrigation system.

The experimental treatments consisted of three humic acid levels: no application (A0), application of 37 mg organic carbon kg^{-1} soil (A1), and application of 75 mg organic carbon kg^{-1} soil (A2), combined with three soil moisture depletion levels (20%, 40%, and 60%) of available water.

The results showed that the seasonal crop water consumption at the 20% depletion level reached 300.88, 278.14, and 272.52 mm $season^{-1}$ for A0, A1, and A2, respectively. Thus, humic acid application achieved water savings of 22.74 mm and 28.36 mm under A1 and A2, respectively, compared with the control treatment. At the 40% depletion level, water consumption values were 301.82, 277.09, and 262.15 mm $season^{-1}$, corresponding to water savings of 24.73 and 39.67 mm under A1 and A2, respectively. At the 60% depletion level, the corresponding values were 301.18, 283.53, and 263.43 mm $season^{-1}$, resulting in water savings of 17.65 and 37.75 mm under A1 and A2, respectively.

The results also indicated a significant improvement in total tuber yield, which reached 42.58 Mg ha^{-1} under A2 compared with 37.56 Mg ha^{-1} in the control treatment. Moreover, water use efficiency increased to 0.160 Mg mm^{-1} $season^{-1}$ under A2 compared with 0.124 Mg mm^{-1} $season^{-1}$ under A0. The highest water use efficiency was recorded under the interaction treatment (D1A2), reaching 0.176 Mg mm^{-1} $season^{-1}$.

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Introduction

Water availability is a limiting factor for the sustainability of agricultural production, particularly in arid and semi-arid regions. Competition for water resources, coupled with climate change and rapid population growth, has intensified the negative impacts on agricultural activities and reduced the share of water available to many countries worldwide, a situation commonly referred to as water scarcity. Therefore, rationalizing water consumption through scientific irrigation practices, such as determining irrigation water applications based on soil water depth and appropriate soil moisture depletion levels that do not induce plant stress, can positively influence soil properties. Moreover, improving the physical characteristics and properties of soil is no less important than the adoption of scientific irrigation practices and technologies (7).

The scarcity and limited availability of freshwater resources have encouraged researchers to develop innovative irrigation methods and management practices. Among the most important of these approaches is exposing crops to controlled water stress during specific growth stages, which does not necessarily result in a significant reduction in yield when soil and crop conditions are scientifically managed. Such practices can contribute to water conservation and allow the saved water to be utilized for agricultural expansion purposes (12).

Humic substances, particularly humic and fulvic acids, are the principal components of organic matter extracts. Their proportions vary according to the type of parent organic material, as well as the duration and nature of its decomposition. In addition, organic matter extracts contain other amino acids and are characterized as mixtures of aromatic and aliphatic compounds that are resistant to decomposition and possess high molecular weights. These substances have been widely used in various agricultural applications because of their ability to improve soil physical properties and increase soil water-holding capacity (4).

Proper water management and efficient utilization are among the major priorities in arid and semi-arid regions. One of the most effective management practices is controlling the amount of water applied during each irrigation event according to the soil's water-holding capacity and the crop's requirements at different growth stages, thereby achieving high productivity while minimizing water losses (13).

Crop water consumption is defined as the total quantity of water utilized by the plant–soil system, including water lost from the soil surface through evaporation, water lost from the aerial parts of the plant through transpiration, and the water used in building plant tissues. Crop water consumption is generally considered equivalent to evapotranspiration (ET) when the amount of water retained within plant tissues at the end of the growing season does not exceed 1% of the total seasonal losses through evaporation and transpiration. Crop water consumption can be estimated using both direct and indirect methods (3).

Humic acids are considered soil biostimulants that contribute directly to improving soil–water relationships. They increase field capacity and enhance soil structure, thereby reducing water losses through deep percolation and surface runoff. Furthermore, their application improves water and nutrient uptake efficiency by stimulating root growth and enhancing cell membrane activity. These effects help reduce soil moisture depletion during crop growth stages. In potato cultivation, studies have shown that the application of humic acids improves water use efficiency and reduces total crop water consumption by enhancing the plant's ability to utilize available soil moisture and alleviate water stress. Consequently, a better balance between crop productivity and water consumption can be achieved, particularly under semi-arid conditions, while contributing to the achievement of sustainability goals (10).

Irrigation scheduling is considered one of the most important water management strategies in agricultural fields and aims to ensure the efficient application of irrigation water without wastage. It has been reported that irrigation scheduling plays a critical role in managing irrigation water with maximum efficiency, as proper scheduling reduces yield losses by minimizing water stress that may affect crop growth. The primary objectives of irrigation scheduling are to determine when irrigation should be applied and how much water should be supplied. Therefore, “when” refers to the timing of irrigation, whereas “how much” refers to the quantity of water that should be added to the soil and the depth of soil to be replenished, in order to avoid excessive irrigation that may negatively affect both soil and crop performance (18).

Accurate determination of crop water consumption is of great importance because it provides essential information required for the planning and design of irrigation and strategic water management projects. It also helps ensure adequate water supplies to meet crop water requirements, particularly in regions suffering from water scarcity, thereby improving water utilization efficiency. Furthermore, information on crop water consumption is crucial for developing suitable irrigation schedules and assessing crop yield per unit of water consumed, which is an important indicator of water productivity (11).

Materials and Methods

A field experiment was conducted during the spring growing season of 2025 at the First Agricultural Research Station (Al-Bu'aitha), College of Agriculture, University of Anbar, located in Ramadi District, Anbar Governorate, Iraq (43°48′10″ E, 33°26′40″ N). The experiment was established on a sandy clay loam (SCL) soil. Morphologically, the experimental soil was classified as *Typic Torrifluvents* according to the USDA Soil Taxonomy system (Soil Survey Staff, 2014).

Before establishing the field experiment, several soil samples were collected from the experimental site, thoroughly mixed to form a composite sample representative of the field at a depth of 0–30 cm. The sample was air-dried and passed through a 2-mm sieve for the determination of selected physical and chemical soil properties that require sieving prior to analysis. Some of the physical and chemical characteristics of the experimental soil before planting are presented in Table (1).

Table 1. Some physical and chemical properties of the soil before planting at a depth

Property	Value	Units	Characteristic		**Value**	
Sand	684	%	pH		7.14	
Silt	112		EC		1.62	**dS m^{-1}**
Clay	204		Soil organic matter		6.2	**g kg^{-1}**
Textural class of soil	Sandy Clay Loam		(CaCO3)		236	
Bulk density	1.38	Mg m^{-3}	(CaSO4)		10.56	
Particle density	2.55		Soluble cations	Calcium	5.20	**meq L^{-1}**
Soil porosity	45.88	%		Magnesium	3.80	
Basic infiltration rate	4.8	cm h^{-1}		Sodium	5.20	
Saturated hydraulic conductivity (Ks)	5.2			Potassium	1.4	
Mean Weight Diameter	0.405	mm	**Soluble anions**	Chloride	6.80	
Volumetric water content (θ)				Sulfate	7.5	
tension (bar)	Value	Units		Bicarbonate	1.67	
0.33Under Field Capacity Conditions	29.3	%		Carbonate	Nill	
1	23.7		Available phosphorus		10.6	mg kg^{-1}
3	19.4		Available potassium		128.5	
5	17.4		Available nitrogen		12.3	
15 Near the Permanent Wilting Point Permanent Wilting Point	13.8		**#Soil–water extract at a 1:1 ratio**			
Available water	15.5					

The experiment included the following factors:

Factor A: Humic Acids Addition (A)

Three levels of humic acid application were investigated:

- **A$_0$:** No humic acid addition (control).
- **A$_1$:** Addition of 37.5 mg organic carbon (OC) kg^{-1} soil.
- **A$_2$:** Addition of 75 mg organic carbon (OC) kg^{-1} soil.

Humic acids were applied to the soil through the irrigation system to a depth of 30 cm, two weeks before planting, as a single application. The applied organic extract was a liquid material containing a mixture of several organic acids.

Factor D: Moisture Depletion (D)

Three levels of soil moisture depletion were studied:

- **D$_1$:** Irrigation at 20% depletion of available water (AW).
- **D$_2$:** Irrigation at 40% depletion of available water.
- **D$_3$:** Irrigation at 60% depletion of available water.

The experimental treatments were arranged in a **split-plot layout** within a **Randomized Complete Block Design (RCBD)** with three replicates. Potato (*Solanum tuberosum* L.) tubers, cv. **Burren**, were planted on 26 January 2025 at a depth of 0.10–0.15 m. Twenty-four tubers were planted in each experimental unit, with a spacing of 0.25 m between tubers and 1.0 m between ridges. Each ridge consisted of three planting rows.

Mineral fertilizers were applied at rates of 300, 300, and 400 kg ha^{-1} of N, P, and K, respectively, according to the recommended fertilization program (1). Fertilizers were applied in two split doses. The first application consisted of the entire phosphorus fertilizer and a portion of the nitrogen fertilizer incorporated into the surface soil layer before planting. The second application consisted of the potassium fertilizer and the remaining nitrogen fertilizer, which were applied one month after plant emergence (6).

The crop growth period was divided into five developmental stages, as presented in Table (2).

Table 2. Growth stages, growth duration, number of days, and root depth.

Growth stages	Time duration	Number of days	Depletion levels	Rooting depth		
				A0	**A1**	**A2**
plant emergence	**-01/26 03/11**	**43**	**%40**	**17**	**17**	**17**
Vegetative Growth Stage	**-03/12 03/31**	**20**	**%20**	**18**	**18**	**18**
			%40	**19**	**19**	**23**
			%60	**20**	**20**	**24**
Tuber Initiation Stage	**-04/01 04/22**	**22**	**%20**	**23**	**19**	**24**
			%40	**26**	**27**	**31**
			%60	**27**	**31**	**34**
Tuber Bucking Stage	**-04/23 05/17**	**25**	**%20**	**30**	**30**	**34**
			%40	**33**	**35**	**38**
			%60	**37**	**39**	**40**
Maturation Stage	**-05/18 05/27**	**10**	**%20**	**34**	**36**	**37**
			%40	**38**	**43**	**47**
			%60	**46**	**47**	**50**

Based on the soil moisture retention curve, the volumetric soil water content at **field capacity (FC)** and **permanent wilting point (PWP)** was determined as presented in Table (1). The equation proposed by **Kovda (9)** was used to calculate the depth of available water in the effective root zone as follows:

$$\mathbf{d} = \frac{\theta_{\mathbf{fc}} - \theta_{\mathbf{pwp}}}{\mathbf{100}} * \mathbf{D} \ldots\ldots\ldots\ldots\ldots.(1)$$

where:

- *d* = depth of available water within the root zone (cm),
- *θFC* = volumetric soil water content at field capacity (%),
- *θPWP* = volumetric soil water content at permanent wilting point (%),
- *D* = effective rooting depth (cm).

The depth of irrigation water applied per irrigation event at 20%, 40%, and 60% depletion levels of available water was calculated using the following equations:

$$\mathbf{d0.20 = (d\times\frac{20}{100}) \ldots\ldots\ldots\ldots\ldots\ldots (2)}$$

$$\mathbf{d0.40 = (d \times\frac{40}{100}) \ldots\ldots\ldots\ldots\ldots\ldots (3)}$$

$$\mathbf{d0.60 = (d\times\frac{60}{100})} \ \ldots\ldots\ldots\ldots\ldots\ldots \ \mathbf{(4)}$$

The calculated depths of irrigation water corresponding to the different moisture depletion levels are presented in the previous table.

The irrigation duration was calculated using the following equation:

Q*t=A*d..............................(5)

where:

- Q = discharge rate of the irrigation system,
- t = irrigation time,
- A = irrigated area,
- d = depth of water applied.

Irrigation scheduling was determined using calibrated soil moisture sensors. Sensor readings were monitored continuously, and irrigation water was applied whenever the predetermined depletion level was reached. Figure (1) illustrates the calibration relationship between sensor readings and the gravimetric soil moisture content.

Crop water consumption (evapotranspiration) was estimated using the water balance equation reported by reference (8):

P+I = ET + R+ ΔW +DP + IN ……………(6)

where:

- P = precipitation,
- I = irrigation water applied,
- ET = evapotranspiration (crop water use),
- R = surface runoff,
- ΔW = change in soil water storage,
- DP = deep percolation losses,
- IN = net lateral inflow.

To maintain uniform moisture stress treatments among experimental units, all plots were covered whenever rainfall was expected. Consequently, the precipitation term (P) in the water balance equation was assumed to be zero throughout the experimental period.

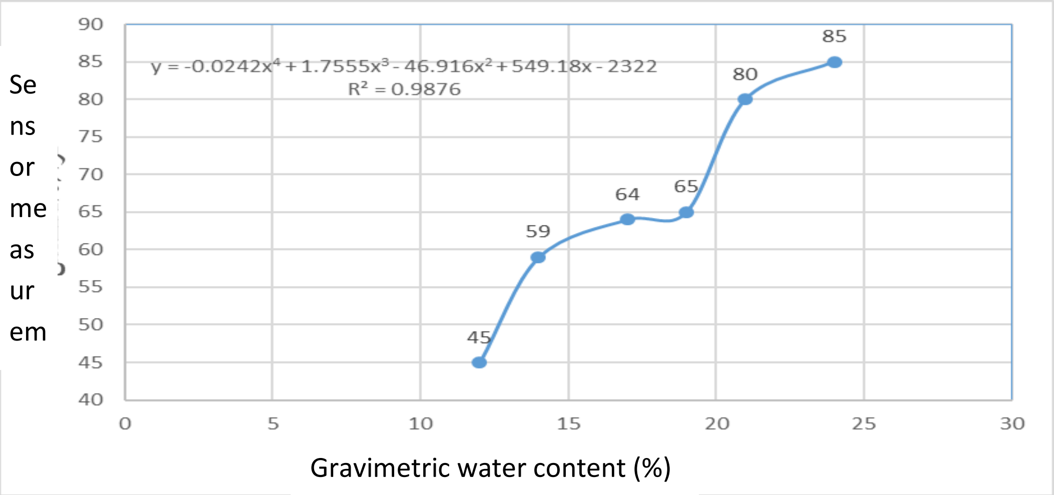

Figure 1. Representation of sensor calibration in field soil conditions.

Crop water use efficiency (WUE) was estimated using the equation reported by reference (16), which is calculated by dividing the total crop yield (t ha⁻¹) by the total volume of applied irrigation water (m³ season⁻¹), as follows:

$$\mathrm{WUE} = \frac{\mathrm{Y}\ (t\ \mathrm{ha}^{-1})}{\mathrm{W\,A}\ (\mathrm{mm}\ \ sa^{-1})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Results and Discussion

1. Water Consumption

Table (3) presents the water requirements of potato (*Solanum tuberosum* L., cv. Burren) from 26/1/2025 to 27/5/2025. The results show the irrigation water depths applied under different humic acid levels (0, 37.5, and 75 mg OC kg^{-1} soil) and soil moisture depletion levels (20, 40, and 60% of available water). Irrigation depths were calculated based on the soil moisture retention curve, while irrigation scheduling was controlled using calibrated soil moisture sensors.

The highest irrigation water depth (110.67 mm) was recorded during the pre-emergence (sprouting) stage, which may be attributed to the longer duration of this stage (43 days) compared with other growth stages.

Treatments	**ET**	**P**	**I**	**R**	**ΔW**	**Dp**	**In**
D1A0	**300.88**	**0**	**323.68**	**0**	**22.6**	**0.20**	**0**
D1A1	**278.14**	**0**	**303.52**	**0**	**25.2**	**0.18**	**0**
D1A2	**272.52**	**0**	**300.08**	**0**	**27.4**	**0.16**	**0**
D2A0	**301.82**	**0**	**317.72**	**0**	**15.5**	**0.40**	**0**
D2A1	**277.09**	**0**	**295.17**	**0**	**17.7**	**0.38**	**0**
D2A2	**262.15**	**0**	**282.62**	**0**	**20.1**	**0.37**	**0**
D3A0	**301.18**	**0**	**314.86**	**0**	**12.8**	**0.88**	**0**
D3A1	**283.53**	**0**	**298.80**	**0**	**14.4**	**0.87**	**0**
D3A2	**263.43**	**0**	**280.29**	**0**	**16**	**0.86**	**0**

Overall seasonal irrigation water application varied according to moisture depletion levels and humic acid treatments. At 20% depletion, total applied water reached 339.86 mm under A_0 (control), while it decreased to 318.69 and 315.08 mm under A_1 and A_2, respectively, representing reductions of 6.2% and 7.2%.

At 40% depletion, seasonal irrigation water amounted to 333.60, 310.49, and 296.79 mm for A_0, A_1, and A_2, respectively, corresponding to reductions of 6.9% and 11.0%.

At 60% depletion, values reached 330.60, 313.73, and 294.30 mm for A_0, A_1, and A_2, respectively, with reductions of 5.1% and 10.9%.

The inverse relationship between moisture depletion levels and irrigation water use is evident. Increasing depletion levels bring soil moisture closer to the permanent wilting point, whereas lower depletion levels maintain soil moisture near field capacity, resulting in shorter irrigation intervals and higher total water use (3).

Table (3) also indicates variation in irrigation frequency across treatments. At 20% depletion, the number of irrigations reached 36 and 33 under A_1 and A_2, respectively, compared with 36 irrigations under A_0. At 40% depletion, irrigation events were 21, 19, and 17 for A_0, A_1, and A_2, respectively, while at 60% depletion they were

Moreover, differences in available soil water were observed due to humic acid application. At 20% depletion, available water increased by 21.16 and 24.77 mm under A_1 and A_2, respectively, compared with A_0. At 40% depletion, increases reached 23.10 and 36.81 mm, while at 60% depletion, gains were 16.86 and 36.03 mm for A_1 and A_2, respectively. This indicates that humic acids enhanced soil water-holding capacity, allowing better utilization of stored soil moisture, which may be used for expanding irrigated area or supporting additional crops.

Table (4) shows seasonal crop evapotranspiration (ET) of potato. Under A_0, ET values were relatively stable across depletion levels (300.88, 301.82, and 301.18 mm $season^{-1}$ for 20, 40, and 60%, respectively). In contrast, humic acid application reduced ET, with values of 278.14, 277.09, and 283.53 mm $season^{-1}$ under A_1, and 272.52, 262.15, and 263.43 mm $season^{-1}$ under A_2 for the respective depletion levels.

The reduction in water consumption under humic acid treatments can be attributed to improvements in soil structure, increased effective porosity, and enhanced field capacity, which improve soil water retention in the root zone. Consequently, losses due to evaporation and deep percolation are reduced, leading to higher water use efficiency. Additionally, humic acids improve plant physiological performance, contributing to more efficient water utilization.

Table 3. Water requirement of potato crop under different application levels.

Growth stages	**Depletion levels**	**Number of irrigations**	**Depth of irrigation water per application (mm)**	**Leaching water depth (mm)**	**Depth of applied water (mm)**	**Total depth of applied water (mm)**

		A_0	A_1	A_2	A_0	A^1	A_2	A_0	A_1	A_2	A_0	A_1	A_2	A_0	A_1	A_2
plant emergence	40%	10	10	10	10.54	10.54	10.54	0.527	0.527	0.527	105.4	105.4	105.4	110.67	110.67	110.67
Vegetative Growth	20%	6	6	6	5.58	5.58	5.58	0.279	0.279	0.279	33.48	33.48	33.48	35.15	35.15	35.15
	40%	2	2	2	11.78	11.78	14.26	0.589	0.589	0.713	23.56	23.56	28.52	24.73	24.74	29.94
	60%	2	2	2	18.6	18.6	22.32	0.93	0.93	1.116	37.2	37.2	44.64	39.06	39.06	46.87
Tuber Initiation	20%	8	6	5	7.59	6.684	9.64	0.379	0.334	0.482	60.72	40.1	48.24	63.75	42.11	50.65
	40%	3	3	2	17.16	18.997	24.92	0.858	0.949	1.246	51.48	56.99	49.84	54.05	59.84	52.34
	60%	2	2	2	26.73	32.717	41	1.336	1.636	2.05	53.46	65.43	82	56.13	68.71	86.11
Tuber Bucking	20%	8	7	5	9.9	10.554	13.66	0.495	0.527	0.683	79.2	73.88	68.34	83.16	77.57	71.75
	40%	4	2	2	21.78	24.626	30.552	1.089	1.231	1.527	87.12	49.25	61.1	91.47	51.71	64.15
	60%	2	1	1	36.63	41.161	48.24	1.832	2.058	2.412	73.26	41.16	48.24	76.92	43.22	50.65
Maturation	20%	4	4	3	11.22	12.665	14.87	0.561	0.633	0.743	44.88	50.66	44.62	47.12	53.19	46.85
	40%	2	2	1	25.08	30.255	37.788	1.254	1.512	1.889	50.16	60.51	37.78	52.66	63.54	39.67
	60%	1	1	0	45.54	49.604	0	2.277	2.48	0	45.54	49.6	0	47.817	52.08	0
Total	**20%**	**36**	**33**	**29**	**44.83**	**46.023**	**54.31**	**2.242**	**2.301**	**2.715**	**323.68**	**303.52**	**300.08**	**339.86**	318.69	**315.08**
	40%	**21**	**19**	**17**	**86.34**	**96.198**	**118.06**	**4.317**	**4.801**	**5.903**	**317.72**	**295.71**	**282.66**	**333.6**	310.49	**296.79**
	60%	**17**	**16**	**15**	**138.04**	**152.62**	**122.1**	**6.902**	**7.631**	**6.105**	**314.86**	**298.8**	**280.28**	**330.6**	313.73	**294.3**

2. Total Yield

Table (5) illustrates the effect of humic acid application and soil moisture depletion levels on the total yield of potato. The results indicate that humic acid application significantly increased total yield. The highest yield was recorded under A_2 treatment, reaching 42.58 Mg ha^{-1}, with an increase of 13.4% compared with the control (A_0), which recorded 37.56 Mg ha^{-1}. The A_1 treatment produced 40.76 Mg ha^{-1}, corresponding to an increase of 8.5% relative to A_0.

This increase may be attributed to the direct effect of humic acids in the rhizosphere through improving soil physical and chemical properties, enhancing nutrient availability, and stimulating root nutrient uptake (15).

Regarding soil moisture depletion levels, the results show that reducing depletion levels significantly increased total yield. The highest yield (45.62 Mg ha^{-1}) was recorded under D_1, followed by D_2 (41.51 Mg ha^{-1}), while the lowest yield (33.78 Mg ha^{-1}) was observed under D_3. This improvement can be explained by enhanced water use efficiency, as maintaining soil moisture within the optimal range promotes root activity and nutrient uptake without exposing plants to severe water stress that negatively affects tuber formation. These findings are consistent with those reported by (2).

The interaction between humic acid application and soil moisture depletion levels showed that the highest yield was achieved under the combined treatment D_1A_2 (48.11 Mg ha^{-1}), whereas the lowest yield was recorded under D_3A_0 (31.47 Mg ha^{-1}), with an increase of 44.9%.

The interaction effect indicates that the combined application of humic acids and low soil moisture depletion significantly improved total potato yield due to the synergistic effects of enhanced soil properties and adequate water availability throughout the growth period. Humic acids improved soil structure, increased water and nutrient retention capacity, and stimulated plant physiological activity, while low depletion levels maintained soil moisture close to field capacity. This provided a favorable environment for root development and sustained nutrient and water uptake without exposing plants to water stress. Consequently, water and nutrient use efficiency improved, leading to better tuber formation, increased tuber weight, and ultimately higher total yield compared with other treatments.

Table 5. Effects of humic acid application and soil moisture depletion levels on total yield (Mg h^{-1}).

Treatments	**D1**	**D2**	**D3**	**Mean values of A**
	Mean values of A*D			
A0	**43.52**	**37.71**	**31.47**	**37.56**
A1	**45.23**	**42.93**	**34.13**	**40.76**
A2	**48.11**	**43.89**	**35.73**	**42.58**
Mean values of D	**45.62**	**41.51**	**33.78**	
LSDA	**2.115**	**LSD D**	**2.698**	
LSD A*D	**4.063**			

3. Water Use Efficiency

Table (6) illustrates the effect of humic acid application and soil moisture depletion levels on water use efficiency (WUE). The results show a significant increase in WUE with humic acid application. The highest values were recorded under A_2, A_1, and A_0 treatments, reaching 0.160, 0.146, and 0.124 t mm^{-1} season^{-1}, respectively, with increases of 29% and 17.7% compared with the control (A_0).

This improvement can be attributed to the ability of humic substances to enhance soil physical properties and increase soil water-holding capacity, thereby reducing water losses through evaporation and deep percolation (17).

Regarding soil moisture depletion levels, the results indicate a significant increase in WUE with decreasing depletion levels. Values of 0.161, 0.149, and 0.120 t mm^{-1} season^{-1} were recorded under D_1, D_2, and D_3, respectively, with increases of 34.1% and 24.1%.

This increase in WUE under lower depletion levels may be explained by the reduction of water stress intensity. Under high depletion levels, longer irrigation intervals and larger water application events lead to reduced water uptake efficiency. In contrast, frequent irrigation with smaller amounts of water maintains soil moisture closer to optimal levels, enhancing nutrient uptake and improving crop productivity per unit of water applied (5).

The interaction between humic acid application and soil moisture depletion levels showed significant differences among treatments. The highest WUE was recorded under D_1A_2 (0.176 t mm^{-1} season^{-1}), whereas the lowest value was observed under D_3A_0 (0.104 t mm^{-1} season^{-1}), representing an increase of 69.5%.

This result indicates a strong synergistic effect between humic acid application and low soil moisture depletion. The combination of improved soil structure, enhanced water retention, and optimal soil moisture availability created favorable conditions for root development and physiological activity, leading to higher yield production per unit of water consumed.

Table 6. Experimental treatments for water use efficiency (t mm^{-1} season^{-1})

Treatments	**D1**	**D2**	**D3**	**Mean values of A**
	Mean values of A*D			
A0	**0.144**	**0.124**	**0.104**	**0.124**
A1	**0.162**	**0.154**	**0.12**	**0.146**
A2	**0.176**	**0.167**	**0.135**	**0.16**
Mean values of D	**0.161**	**0.149**	**0.12**	
LSDA	**0.007**	**LSD D**	**0.009**	
LSD A*D	**0.014**			

The study concludes that the application of humic acids, particularly at a rate of 75 mg kg^{-1} soil, combined with low soil moisture depletion (20%), led to a reduction in irrigation water consumption by approximately 11%. This treatment also improved water use efficiency and increased potato productivity under arid and semi-arid conditions. These findings are aligned with the Sustainable Development Goals (SDGs), particularly **SDG 6 (Clean Water and Sanitation)** through reducing water consumption and improving water use efficiency, **SDG 2 (Zero Hunger)** by enhancing crop productivity, and **SDG 13 (Climate Action)** through improving crop adaptation to drought conditions. In addition, the results support **SDG 15 (Life on Land)** by improving soil properties through the application of humic substances.

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