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Impact of reclaimed wastewater on alfalfa production under different irrigation methods

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ABSTRACT

The effect of different irrigation methods (sprinkler, surface, surface-drip, and subsurface-drip) using treated wastewater, on alfalfa yield quantity and quality, was studied under semi-arid conditions. Randomized complete block design considering irrigation methods on 5 × 5 m plots replicated four times. Applied irrigation water was based on the Penman–Monteith equation using the FAO Cropwat software and accounting for the efficiencies of used irrigation systems. Surface irrigation gave the highest alfalfa fresh yield without significant difference compared to subsurface-drip. Average fresh production was 123, 120, 109, and 91 tons/h for surface, subsurface-drip, surface-drip, and sprinkler irrigation, respectively. Alfalfa fresh weight from subsurface-drip irrigation was 32 and 10% higher compared to sprinkler and surface-drip irrigation. Alfalfa dry weight from subsurface-drip irrigation was 10, 21, and 47% higher compared to surface-drip, surface, and sprinkler irrigation, respectively. N percentage in alfalfa leaves was significantly lower by 12% under subsurface-drip irrigation as compared to the other irrigation methods. *Escherichia coli* (*E. coli*) and fecal coliform (FC) were not detected on alfalfa leaves using subsurface-drip irrigation. *E. coli* and FC counts were high on leaves using sprinkler and surface irrigation. Subsurface-drip irrigation may be adapted as an efficient irrigation method when using non-conventional water under semi-arid conditions.

Key words: alfalfa, *E. coli*, irrigation, sprinkler, subsurface, wastewater

HIGHLIGHTS

- Irrigation study: Examined methods using treated wastewater in semi-arid areas.
- Subsurface-drip: Tops in dry yield, matches in fresh yield.
- Health benefits: Subsurface-drip reduces *E. coli* and fecal coliform on alfalfa.
- Smart water use: Advocates calculated use with FAO Cropwat insights.
- Alternative water: Recommends subsurface-drip for treated wastewater in semi-arid regions.

1. INTRODUCTION

The Mediterranean is among the most water-scarce regions. Jordan is the second-most water-scarce country in the world. Jordan's annual renewable water resources average is less than 100 m^3 per capita, significantly below the threshold of 500 m^3 per person which defines severe water scarcity (Aboelnga *et al.* 2018). Population increases, climate change, urbanization, over-exploitation, and water quality degradation are all factors that exacerbate the problem of water scarcity, especially in arid and semi-arid regions (Makarigakis & Jimenez-Cisneros 2019). Agriculture is the area most affected by water scarcity since it is the highest water consumer, using about 70% of globally available freshwater (Harmanny & Malek 2019). It is estimated that the gross irrigation requirements will face an increase of 4–18% if irrigated agriculture does not adapt to water scarcity conditions (Makarigakis & Jimenez-Cisneros 2019). Mediterranean farmers have been responding and adapting to changes in their environment throughout history. Different adaptation strategies have been reported, including switching to more efficient irrigation systems (Sese-Minguez *et al.* 2017). Farmers often directly target improving their irrigation systems by changing to more efficient irrigation methods and adjusting their irrigation scheduling (Harmanny & Malek 2019).

Improving water use efficiency and identifying alternative resources such as non-conventional water is imperative. Reusing reclaimed wastewater (RWW) for irrigation has gained significance as an alternative resource for meeting the growing water demands for agriculture and reducing the pressure on limited existing freshwater (Khawla *et al.* 2019). However, the reuse requires adapted management and special agricultural practices in order to avoid environmental and health risks. Among the agricultural practices that allow the optimization and preservation of nutrients and water are adapted irrigation methods, including the surface-drip irrigation method (Mahmoudi *et al.* 2020). Many studies have been conducted to determine the advantages and benefits of utilizing treated wastewater using surface-drip irrigation compared to other irrigation methods (Hidri *et al.* 2013; Rawashdeh *et al.* 2021). These studies recommended the use of surface-drip irrigation, as it showed a low level of contamination and saved water. As a rule, treated wastewater standards mandate the use of surface-drip irrigation when irrigation is restricted. The Jordanian standards for reclaimed domestic wastewater (JS893/2006) state that agricultural reuse of treated wastewater must be carried out using surface-drip irrigation when the treated wastewater is mainly used to irrigate fodder crops such as alfalfa and barley. JS893/2006 prohibits the use of sprinkler irrigation except for overnight golf course irrigation. Currently, in Jordan, some fodder crop farmers have stopped using surface-drip and switched to sprinkler irrigation, 'despite its prohibition'; their reasons are related to the high initial cost, maintenance, and labor needed for surface-drip irrigation. There is no need also to remove the irrigation system at the harvest time, which is mandatory for surface-drip irrigation. However, studies related to sprinkler irrigation using treated wastewater are very limited. The effect of using surface (flood), surface-drip, and sprinkler irrigation methods with treated wastewater on soil trace elements was studied. The results indicated that surface-drip and subsurface-drip irrigation could reduce soil contamination with trace elements in comparison to surface (flood) and sprinkler irrigation (Khaskhoussy *et al.* 2015). In recent years, the trend has shifted toward subsurface-drip irrigation. This method appears to reduce a large number of problems related to irrigation using treated wastewater in agriculture (Rawashdeh *et al.* 2021). All irrigation methods need good, careful management and maintenance when using treated wastewater.

Although wastewater reclamation has distinguished itself as a useful approach to ensuring a sustainable water supply in arid and semi-arid regions, there are still some concerns about the sustainability of wastewater-irrigated agriculture (Harmanny & Malek 2019). In addition, farmers' attitudes toward wastewater reuse and the impacts of its application on sustainability are very important.

With respect to this, this study came to investigate the impacts of different irrigation methods, namely: surface-drip, surface (flood), sprinkler, and subsurface-drip, on alfalfa crop quantity and quality using treated wastewater under semi-arid conditions. Given alfalfa's substantial water demands, its selection as the focal point of this research offers a strategic avenue to assess irrigation efficiency and water management methodologies. Through this analysis, we aim to derive actionable insights for enhancing water utilization across similar agricultural contexts facing environmental challenges. Moreover, the investigation delineates the capacity of alfalfa to adapt to varying water qualities and its contribution toward fostering sustainable farming practices amid prevalent water shortages (Hidri *et al.* 2013; Rawashdeh *et al.* 2021).

2. METHODS

This experiment was conducted from December 2020 to October 2021 at Ramtha Experimental Station for Treated Wastewater Studies of the National Agricultural Research Center (NARC), located at Ramtha area, 88 km north of Amman, Jordan. Ramtha (altitude 484 m, latitude 32°35′ N, and longitude 35°59′ E) has an average annual rainfall of about 275 mm.

A randomized complete block design was used to investigate the impact of using RWW with four different irrigation methods: sprinkler, surface (flood), surface-drip, and subsurface-drip. The irrigation methods were assigned to completely randomized experimental plots of 5×5 m, with 3 m spacing between plots. The four irrigation methods were each replicated four times; therefore, the total number of plots was 16. Alfalfa seeds were planted at a rate of 70 kg/ha, with alfalfa harvested four times during the experiment period, on May 18, June 6, June 28, and August 3, 2021.

Initial composite soil samples at two depths (20–25 cm and 25–50 cm) were analyzed to characterize the soil condition prior to the experiment. The textural class of the soil was clay (with an average clay content of more than 50%), with low salinity (<1.0 dS/m), and soil pH slightly alkaline with an average of 8.4. The soil had good fertility with high potassium content reaching more than 700 mg/L. Phosphorus, nitrogen, and the organic matter reached 20 mg/L, 0.09%, and 1.25%, respectively. Moreover, the soil showed low values for trace elements (Cu, Fe, Zn, and Mn), with values ranging from less than 1.0 mg/L for Fe to about 6.0 mg/L for Zn. The soil had very low concentrations of heavy metals (Cr, Cd, Co, Ni, and Pb), ranging from 0.005 for Cr to less than 1 mg/L for Ni.

Four irrigation methods were used such as sprinkler, surface (flood), surface-drip, and subsurface-drip irrigation. The impact of these irrigation methods was investigated on alfalfa crop irrigated with RWW. The source of irrigation water was the domestic treated wastewater effluent from the Ramtha Secondary Wastewater Treatment Plant (RWTP). The treated wastewater was connected to the experimental site via the main polyethylene irrigation line (75 mm) and was filtered through sand and disc filters after reaching the experimental site and before being used.

Four pop-up sprinklers with discharge rates of 0.1 m^3/h were used, with one sprinkler at each corner of each sprinkler plot. The water pressure was 2–3 bars, the spray distance (radius) ranged from 4.5 to 5 m, with a 90° pattern; the spacing between each adjacent sprinkler and line was 5 m, providing a 100% overlap. In the subsurface-drip irrigation method, the field was leveled and the dripper lines were installed at 25 cm deep with 50 cm between two adjacent dripper lines. The distance between drippers was 30 cm. Dripper lines were GR 16 mm. Pressure compensated non-leakage (PC-NL) drippers with discharge rates of 2 L/h were used. The downstream end of each dripper line was connected to a manifold for convenient flushing. Inlet pressure on each line was about 1 bar. The layout of the surface-drip irrigation was exactly the same as that of the subsurface-drip except for the positions of the dripper lines that were installed on the soil surface.

Irrigation quantity was monitored by four digital water meters, one for each irrigation method. The irrigation intervals for each irrigation method were based on 30% of the available water being depleted, as determined by a Tensiometer reading. Applied irrigation water was calculated based on the Penman–Monteith equation, using the FAO Cropwat software and taking into account an irrigation system efficiency of 60, 70, 85, and 90% for surface (flood), sprinkler, surface-drip, and subsurface-drip irrigation, respectively.

The productivity of alfalfa for each irrigation method in the four replicates was evaluated for each cut. Alfalfa fresh and dried weights were measured. Composite alfalfa leaf samples were collected from the plots to represent the different irrigation methods. The leaf contents of specific macro- and micronutrients and heavy metals (K, P, Ca, Mg, Cl, Na, N, Fe, Cu, Mn, Pb, Zn, Ni, Cd, Cr, and Co) were analyzed according to official methods of analysis of AOAC (Horwitz 2010).

In addition, random alfalfa plant samples were collected from the upper and lower (20 cm) parts of the plant. Samples were collected immediately after ceasing irrigation during the harvesting of each cut. Another set of plant samples was collected 2 weeks after harvesting and air-dried. These samples were gathered mainly to detect biological contaminations; hence, they were analyzed for fecal coliform (FC) and *Escherichia coli* (*E. coli*). Plant samples were collected with high precautions and a high level of hygiene to prevent any disturbance and/or contamination. Collected samples were delivered in a cooler to the NARC laboratory on the same day to prevent any damage and/or contamination. Total coliform and *E. coli* were analyzed and reported as the most probable number (MPN) per gram weight of the plant sample. No special procedures have been taken during the sampling period that could affect the irrigation schedule or productivity values. The treated wastewater used for irrigation in this experiment was sampled and analyzed by the NARC on a bimonthly basis for 6 months. The chemical and biological characteristics of wastewater monitored in this study were biological oxygen demand (BOD_5), chemical oxygen demand (COD), pH, electrical conductivity (EC), Mg, Ca, Cl, Na, K, total phosphorus (TP), total nitrogen (TN), and bicarbonates (HCO_3). The samples were analyzed according to the Standard Methods for the Examination of Water and Wastewater (APHA 1995).

Data were analyzed with analysis of variance (ANOVA) using Statistx 8.1 software. Means were compared using LSD multiple range tests at ($P \leq 0.05$) probability level.

3. RESULTS AND DISCUSSION

3.1. Reclaimed wastewater quality

Results of the chemical and biological characteristics of the RWW used in this study, comparisons between these characteristics and the Jordanian standard for RWW (JS893/2006), the results from a previous study in the same region are shown in Table 1. This study compares the characteristics of RWW with data from previous studies and Yarmouk Water Company records to assess the consistency of RWW quality over time, checks the stability of water treatment processes, and identifies any deviations from Jordanian standards. It helps evaluate potential impacts on agricultural practices and underscores the need for continuous quality monitoring to ensure the safe use of RWW in agriculture. The analysis showed a higher EC value for RWW (2.89 dS/m) as compared to freshwater (1.22 dS/m). The mean values of pH, cations, anions, TN, TP, BOD_5, and COD in the TWW were within the Jordanian standard for treated wastewater reuse irrigation of forage crops. Results of this study mostly compared satisfactorily to previous studies mentioned. However, the average Na in the TWW was 286 mg/L, which is higher than the standard's maximum allowable concentration.

Table 1 | Reported parameters average of chemical and biological characteristics of treated wastewater at the Ramtha wastewater treatment plant

Parameter	This study	Previous study using the same TWW (Ayoub *et al.* 2016)	Yarmouk Water Company records (2019–2020)[a]	Maximum allowable limits in the Jordanian standards JS893:2006[b]
pH	8.54	7.98	7.8	6–9
EC (dS/m)	2.89	2.71	–	–
Ca^{2+} (mg/L)	66.1	71	86	230
Mg^{2+} (mg/L)	45.2	41.3	36	100
Na^{+} (mg/L)	386.2	492.7	375	230
K^{+} (mg/L)	209.2	53.8	–	–
SAR ($mol^{1/2}$ $m^{-3/2}$)	–	11.5	8.6	–
TP (mg/L)	0.44		7.2	30 as (PO_4)
TN (mg/L)	98	45.5	40.8	100
Cl^{-} (mg/L)	34	694.4	538	400
SO_4^{2-} (mg/L)		325	152	500
TSS (mg/L)		39	45.6	–
HCO_3^{-} (mg/L)	6.7	–	360	400
BOD_5 (mg/L)	5	24.9	21.2	300
COD (mg/L)	93	49.3	70.5	500
E. coli (MPN/100 ml)		–	8,800,000	–

[a]The Yarmouk Water Company, the official operator of the Ramtha wastewater treatment plant, has a fixed water quality monitoring program and records.
[b]Forage crops irrigation, according to the Jordanian standard for reclaimed domestic wastewater JS893:2006.

The ions of most concern in using the treated wastewater for irrigation are sodium and chloride. The mean effluent value of Na^{+} for 22 selected Jordanian domestic wastewater treatment plants ranged between 75 and 395 mg/L (Ibrahim 2019). The mean Na^{+} values in the Ramtha, Ekedar, and Mafraq WWTP exceeded the permissible limit of 230 mg/L as per the JS893/2006, and their mean Na^{+} concentrations were 335, 395, and 243 mg/L, respectively. The source of chloride and sodium is usually household detergents; they also increase during domestic usage, especially where water softeners are used. The prolonged use of high Na^{+} water can lead to decreased soil permeability of water and air (Shatanawi & Fayyad 1996).

Table 1 shows that the Cl^{-} was higher than the maximum allowable concentration in the previous studies, and in the results of the Yarmouk Water Company (the official national operator of the Ramtha WWTP). Both Cl^{-} results contradict ours; they may be related to the fact that the final treatment stage in the Ramtha WWTP is chlorination, which was not in use due to maintenance during our water sampling. In general, all the chemical and biological characteristics of the Ramtha TWW quality are satisfactory compared to JS893/2006, except for Na and Cl.

3.2. Crop water requirements using CROPWAT

The crop water requirement for alfalfa cultivation in the Ramtha location was precisely estimated with the CROPWAT software. The software utilized climatic data from the Ramtha research station, including minimum and maximum temperatures, humidity, wind speed, sunlight hours, solar radiation, and estimated potential evapotranspiration (ETo). These variables are crucial for the accurate calculation of evapotranspiration and subsequently the crop water requirement. Table 2 presents the average monthly climatic data alongside the calculated alfalfa crop evapotranspiration:

Table 2 | Monthly average climatic data and alfalfa crop evapotranspiration

Month	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (km/day)	Solar rad (MJ/m²/day)	ETo (mm/day)	Effective precipitation (mm/month)	Alfalfa crop evapotranspiration (mm/month)
January	4	13	73	104	10.7	1.32	45	40.92
February	4.4	14.4	66	112	13.3	1.83	43.5	51.24
March	5.9	17.5	64	104	17.2	2.53	40.4	78.43
April	9.4	23.4	51	130	20.9	3.93	9.9	117.9
May	12.6	28.5	42	147	25.1	5.44	3.3	168.64
June	15.3	30.6	48	164	27	6.11	0.7	183.3
July	17.5	32.2	51	156	26.3	6.13	0	190.03
August	17.8	32.4	53	112	24.5	5.42	0	168.02

The mean values of the climatic variables are critical for an accurate estimation of the crop water requirement. Our analysis considered the average of each climatic parameter monthly to reflect the environmental conditions influencing water demand for alfalfa growth. Notably, the average potential evapotranspiration (ETo) of 4.1 mm/day represents the daily water requirement for alfalfa under typical conditions at the Ramtha site.

The seasonal variations in these climatic variables are significant, as they directly affect the irrigation requirements and crop yield. For instance, during the warmer months, increased temperatures and solar radiation substantially raise the crop's water demand. This necessitates efficient management of irrigation systems to optimize water usage and ensure sustainable alfalfa production.

Based on the calculated alfalfa crop evapotranspiration, we have analyzed and compared water application rates for the different irrigation systems, taking into account each system's efficiency. Table 3 details the monthly water application for each system, highlighting the adaptive strategies employed to optimize water usage in response to actual crop water requirements.

Table 3 | Water application in (mm) for different irrigation systems for irrigating alfalfa

Month	Surface irrigation system	Sprinkler irrigation system	Surface-drip irrigation system	Subsurface-drip irrigation system
January	0	0	0	0
February	0	0	0	0
March	63	54	45	42
April	180	154	127	120
May	276	236	195	184
June	304	261	215	203
July	317	271	224	211
August	280	240	198	187

3.3. Plant productivity

The fresh and dry yield of alfalfa irrigated by RWW varied significantly among the investigated irrigation methods. The results are presented in Tables 4 and 5. Results showed that the highest fresh yield was obtained from surface (flood) and subsurface-drip irrigation, and the least significant fresh yield was obtained from

Table 4 | Fresh weight (tons/h) of alfalfa irrigated by reclaimed wastewater under different irrigation methods

Irrigation methods	1st cut	2nd cut	3rd cut	4th cut	Average	SD	Total[a]
Surface-drip	31.8	22.9	25.6	28.8	27.3	1.6	109.1[c]
Sprinkler	20.3	18.6	23.4	28.5	22.7	0.7	90.8[c]
Subsurface-drip	36.1	21.4	30.9	31.5	30.0	0.8	119.9[c]
Surface (flood)	45.5	22.8	24.6	30.1	30.8	1.1	123.0[a]

[a]Different letters indicate significant differences at $P < 0.05$ by LSD test.

Table 5 | Dry weight (tons/h) of alfalfa irrigated by treated wastewater under different irrigation methods

Irrigation methods	1st cut	2nd cut	3rd cut	4th cut	Average	SD	Total[a]
Surface-drip	4.1	3.0	3.3	3.8	3.6	0.3	14.2[c]
Sprinkler	2.0	1.9	2.4	2.9	2.3	0.1	09.2[c]
Subsurface-drip	4.7	2.8	4.0	4.1	3.9	0.2	15.6[a]
Surface (flood)	4.5	2.3	2.5	3.0	3.1	0.1	12.3[b]

[a]Different letters indicate significant differences at $P < 0.05$ by LSD test.

sprinkler irrigation. The total alfalfa fresh weight productivity was 123, 119.9, 109.1, and 90.8 tons/h for surface (flood), subsurface-drip, surface-drip, and sprinkler methods, respectively. The average increases in the alfalfa dry weight obtained from subsurface-drip irrigation were 10, 21, and 47% compared to surface-drip, surface (flood), and sprinkler irrigation, respectively.

Although surface (flood) irrigation gave the highest yield without a significant difference in comparison to subsurface-drip irrigation, subsurface-drip irrigation allows plants to make better use of the water through the application of water at the root zone; it also reduces deep percolation, evaporation, and surface runoff (Rawashdeh *et al.* 2021). Using wastewater increased the production per unit area and subsequently increased the elements' concentration in both soil and plants.

The results of the alfalfa dry yield are presented in Table 5. The results indicated that the subsurface-drip and surface-drip irrigation methods significantly increase the dry yield compared to surface (flood) and sprinkler irrigation. The average production of dry yield was 15.6 and 14.2 tons/h for subsurface-drip and surface-drip irrigation methods, respectively, and significantly decreased to 12.3 and 9.2 tons/h for surface (flood) and sprinkler irrigation methods, respectively. The average increases in the alfalfa dry weight obtained from subsurface-drip irrigation were 10, 21, and 47% compared to surface-drip, surface (flood), and sprinkler irrigation, respectively. Comparing our results with the previous studies indicated that our alfalfa dry yield production was almost in line with the others for all the irrigation methods used except for sprinkler irrigation, which had a lower yield than the others.

The subsurface-drip irrigation method produced an increased fresh and dry alfalfa yield compared to sprinkler and surface-drip irrigation methods. Large significant differences were found between subsurface-drip irrigation and sprinkler irrigation. However, the differences were smaller when comparing subsurface-drip irrigation to surface (flood) irrigation. These results are because increasing available water in the root zone area enhances growth parameters and consequently increases the yield. Subsurface-drip irrigation increased plant height and number of tillers compared to other irrigation methods (Almarshadi & Ismail 2011). The improvement in soil moisture using subsurface-drip irrigation leads to enhanced plant growth parameters and is therefore reflected in forage yield increases (Fu *et al.* 2021). Similar results with different water qualities and different crops have been reported in other studies (Patel *et al.* 1990; Awad *et al.* 2009; Almarshadi & Ismail 2011). Alfalfa would benefit more than most crops from subsurface-drip irrigation because of its elevated needs for water, mainly after each cut, to start re-growth; hence, subsurface-drip irrigation provides a dominant wet soil condition in the root zone and continuous irrigation right after harvest to encourage rapid re-growth and does not require irrigation suspension before the harvesting to allow for dry soil (Alam & Rogers 2009; Awad *et al.* 2009; Almarshadi & Ismail 2011).

The least alfalfa production was obtained from sprinkler irrigation, which could be attributed to water salinity and higher Na and Cl concentrations in RWW, which significantly affected the crop's leaves, in addition to the high wind speed that affected the experimental area. The efficiency of sprinkler irrigation is greatly reduced because the water distribution can be interrupted and heterogeneously distributed among the cultivated area, resulting in low production. In addition, the area's high evaporation factor meant that less water than required was applied, resulting in yield reduction. Similar results were published (Ismail *et al.* 2018).

3.4. Plant nutrient content

Macro- and micronutrients and heavy metals concentrations in the alfalfa leaves were measured during the experiment in the four alfalfa cuts; their averages are presented in Tables 6 and 7. Alfalfa leaf analysis showed no significant differences in the P, Ca, Cu, Mn, and Pb element concentrations among the four irrigation methods. The K and Mg concentrations were significantly lower in alfalfa leaves irrigated by the surface-drip method as compared to the other three irrigation treatment methods. Na, Cl, and Fe concentrations in the alfalfa leaves were significantly higher by 100, 40, and 100%, respectively; in alfalfa leaves irrigated by sprinkler irrigation as compared to other irrigation methods.

Table 6 | Macronutrients concentration in the alfalfa leaves in the four alfalfa cuts for the different irrigation methods

	N (%)		K (%)		P (%)		Ca (%)		Mg (%)	
Irrigation methods	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Surface-drip	3.55*	1.3	1.79**	0.7	0.29	0.08	1.75	0.6	0.38**	0.3
Surface (flood)	3.53*	0.14	2.14*	0.7	0.30	0.05	1.79	0.6	0.48**	0.17
Subsurface-drip	3.15**	1.2	1.99*	0.5	0.29	0.05	1.74	0.6	0.45*	0.16
Sprinkler	3.48*	1.1	1.98*	0.7	0.31	0.05	1.75	0.8	0.50*	0.18

*,**indicate significant differences at $P < 0.05$ by LSD test.

Table 7 | Micronutrients concentration in the alfalfa leaves in the four alfalfa cuts for the different irrigation methods

	Cl (%)		Na (%)		Fe (mg/L)		Cu (mg/L)		Pb (mg/L)		Zn (mg/L)		Mn (mg/L)	
Irrigation methods	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Surface-drip	1.00**	0.24	0.37**	0.16	222**	78	8	3.1	1.4	1.1	14	5.7	70	15
Surface (flood)	1.08**	0.21	0.36**	0.14	177**	68	7	1.6	0.9	0.7	15	3.1	69	15
Subsurface-drip	1.08**	0.21	0.33**	0.17	190**	53	7	2.3	1.2	0.9	15	3.5	61	5
Sprinkler	1.46*	0.40	0.72*	0.18	459*	313	8	2.2	1.4	0.8	18	5.0	66	15

*,** indicate significant differences at $P < 0.05$ by LSD test.

The N percentage was significantly lower by 12% in alfalfa leaves irrigated using subsurface-drip irrigation in comparison to the other three irrigation methods, which might be related to the higher productivity and biomass of alfalfa when subsurface-drip irrigation is used. Ni was not detected in the first cut; however, it averaged 0.93, 0.57, 0.58, and 0.87 mg/L in the leaves of the second alfalfa cut for surface-drip, surface (flood), subsurface-drip, and sprinkler irrigation, respectively. In the third and fourth alfalfa cuts, the Ni average concentration was below 0.004 mg/L. Cd was either not detected or below 0.004 mg/L for all the irrigation methods. Cr appeared in the leaves of the first and the third cuts, with an average of 0.94 and 1.2 mg/L, respectively. Cr was recorded at less than 0.0054 mg/L in the second and fourth cuts for all the samples. Co concentrations were less than 0.011 mg/L in all the samples, regardless of the irrigation method or the cuts. The concentration of heavy metals in the treated sewage effluents did not exceed the international standards, except for cadmium, which was double the allowable limit (Ibrahim 2019).

Subsurface-drip irrigation has been identified as a superior method for reducing heavy metal uptake in plants compared to surface methods like sprinkler irrigation, which often results in higher metal concentrations due to direct foliar contact (Singh *et al.* 2020). Subsurface-drip irrigation minimizes this risk by delivering water directly to the root zone, thereby limiting the exposure of plant aerial parts to contaminated water and reducing foliar absorption of pollutants (Slamini *et al.* 2022). This targeted water delivery not only enhances water use efficiency but also decreases surface runoff, thereby curtailing the mobilization and spread of heavy metals across the soil surface (Enciso *et al.* 2021). Furthermore, by mitigating evaporation and reducing soil disturbance, subsurface-drip irrigation contributes to improved soil health and structure, which is crucial for long-term agricultural sustainability (Romero *et al.* 2022). The efficiency of subsurface-drip irrigation in optimizing water and nutrient delivery to the plant roots enhances plant growth and resilience, further reducing the propensity for heavy metal uptake and promoting sustainable agricultural practices in regions utilizing RWW for irrigation (Asgari & Cornelis 2015). Rigorous and frequent testing of wastewater, soil, and plants is required in cultivated farms to prevent the translocation of heavy metals in the food chain (Othman *et al.* 2021).

The trend of the metal accumulation by plants seems to be governed by the criteria of essentiality of nutrients and their presence in the soil and water substrate (Khan *et al.* 2011). The soil used in this experiment had very low values of trace elements; for example, the Fe average concentration was less than 1.0 mg/L; thus, the higher value of Fe in alfalfa leaves irrigated by sprinkler irrigation, as shown in Figure 1, might be related to Fe adsorption,

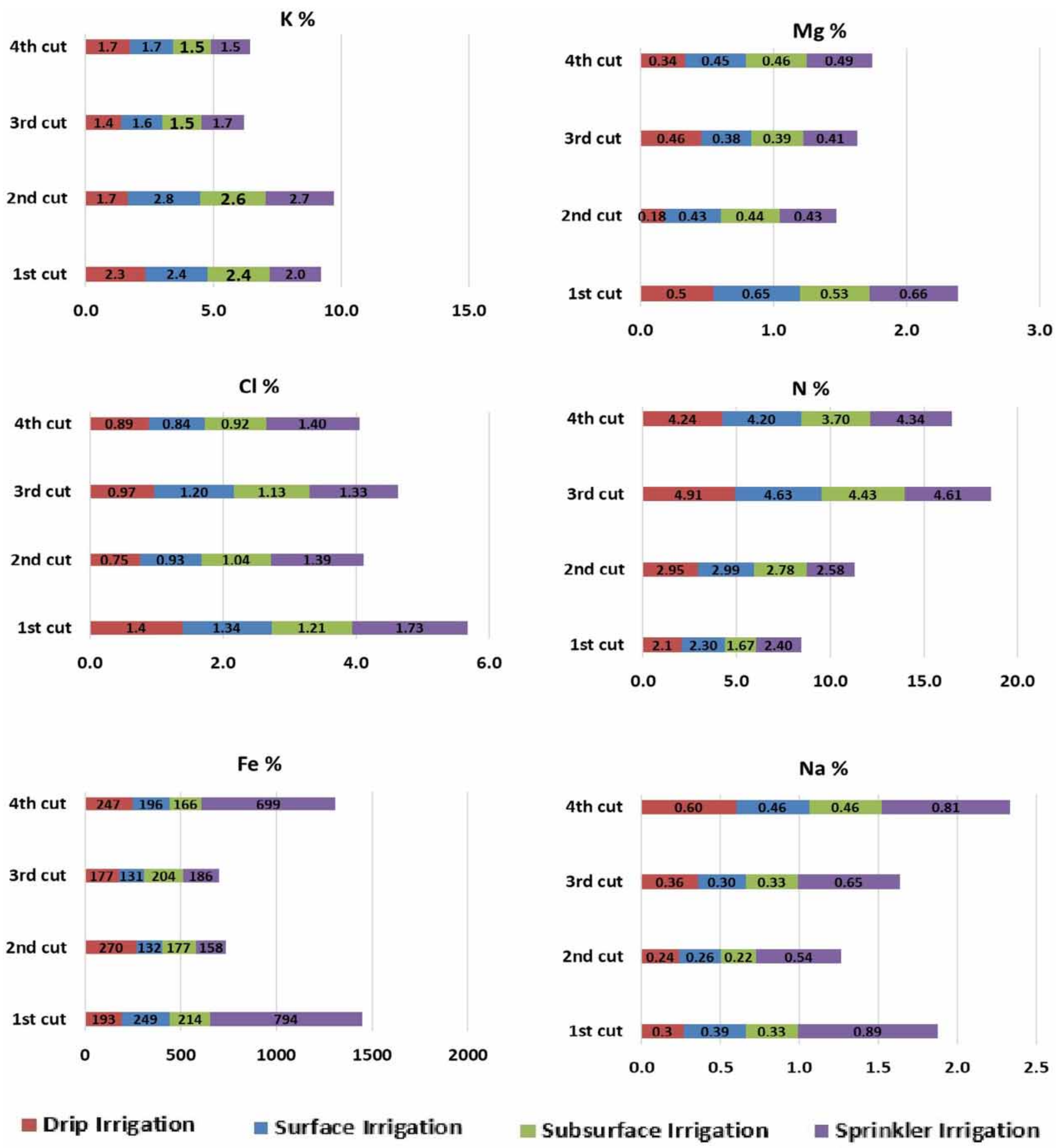

Figure 1 | Concentrations of some elements in the alfalfa leaves in the four alfalfa cuts for the different irrigation methods.

absorption, and accumulation on the surface of the alfalfa leaves due to direct contact with the RWW and enhanced by high evaporation in such a dry area. Na and Cl also accumulated on the surface of alfalfa leaves irrigated by sprinkler in the same manner, facilitated by the high Na and Cl content in the RWW.

Figure 1 shows that Fe and Na accumulated substantially in the first and fourth cuts on the surface of alfalfa leaves irrigated by sprinkler, and the alfalfa leaves were exposed to long irrigation periods before the first and fourth cuts in comparison to the irrigation period of the second and third cuts. The fourth cut occurred 36 days after the third, the third cut occurred 22 days after the second cut, and the second cut occurred 18 days after the first cut. Cl accumulated substantially in the first cut on the surface of alfalfa leaves irrigated by sprinkler, as shown in Figure 1. This result is also related to the high Cl content in the TWW when the Ramtha WWTP's chlorination stage was active before the first cut at the beginning of this experiment.

E. coli and FC are key representative indicators for wastewater microbial pollution. The probability of irrigation water making contact with the upper parts of the alfalfa plant is lower than that of making contact with the lower part. Table 8 shows that neither *E. coli* nor FC was detected on the alfalfa leaves when using subsurface-drip irrigation. However, high *E. coli* and FC counts were present on the leaves irrigated by sprinkler and also in the lower part of the plants when surface (flood) irrigation was used. This indicates a high risk of pathogen presence in sprinkler and surface (flood) irrigation methods with this quality of water.

Table 8 | Most probable number (MPN) per gram dry weight of the alfalfa leaf sample collected immediately after irrigation ceased

	Surface (flood) irrigation method		Subsurface-drip irrigation method		Surface-drip irrigation method		Sprinkler irrigation method	
Parameter	Upper part	Lower part	Upper part	Lower part	Upper part	Lower part	Upper part	Lower part
Escherichia coli (MPN)	<3	3×10^2	<3	<3	<3	<3	20×10^2	$>1,100 \times 10^2$
	<3	4×10^2	<3	<3	<3	<3	20×10^2	4×10^2
	<3	15×10^2	<3	<3	<3	<3	15×10^2	9×10^2
Fecal coliform (MPN)	4×10^2	43×10^2	<3	<3	<3	11×10^2	$>1,100 \times 10^2$	$>1,100 \times 10^2$
	4×10^2	7×10^2	<3	<3	<3	4×10^2	$>1,100 \times 10^2$	23×10^2
	<3	93×10^2	<3	<3	<3	$>1,100 \times 10^2$	$>1,100 \times 10^2$	93×10^2

Results of the surface-drip irrigation show that alfalfa leaves were free from *E. coli* and that the upper parts of the plants were free from FC. The risk of pathogens is still present in the lower part of the plant when a surface-drip system is adapted for TWW irrigation. The fluctuations in *E. coli* and FC counts in the alfalfa leaves are mainly related to the irrigation methods and the location of plant samples (lower vs. upper) and somewhat related to air temperature, water temperature, wind speed, and solar radiation. Regardless of the irrigation method, *E. coli* and FC were not detected on all alfalfa leaf samples collected 2 weeks after harvesting and air-dried per farmers' specifications for use in animal rations.

3.5. Highlighting economic benefits

A comparative analysis of initial investment and long-term economic viability of various irrigation methodologies reveals the potential of subsurface-drip irrigation for sustainable agriculture. While subsurface-drip irrigation necessitates a higher upfront cost (approximately $290/dunum compared to $140/dunum for other systems), its benefits outweigh the initial investment. Firstly, subsurface-drip irrigation boasts a doubled lifespan, significantly reducing long-term replacement costs. Secondly, maintenance expenditures for subsurface-drip irrigation are approximately half those of alternative systems. Additionally, subsurface-drip irrigation eliminates the need for system removal during plowing and harvesting, leading to a 30% reduction in land service expenses.

The most compelling advantage of subsurface-drip irrigation lies in its superior water efficiency. By minimizing soil surface evaporation, subsurface-drip irrigation optimizes water productivity and utilization. This translates not only to increased yield per unit of water but also to a significantly improved benefit-cost ratio compared to other irrigation methods. While the initial outlay for subsurface-drip irrigation might seem higher, the combined benefits of extended lifespan, lower maintenance and operational costs, and exceptional water conservation solidify its economic appeal. This analysis positions subsurface-drip irrigation as a financially sustainable solution, aligning perfectly with the growing focus on agricultural sustainability, particularly in water-scarce regions.

4. CONCLUSIONS

Farmers often directly target improving their irrigation systems by switching to more efficient and practical methods, mainly when using RWW. In Jordan, most fodder crop farmers stopped using surface-drip irrigation (despite its efficiency) and switched to surface (flood) and sprinkler irrigation (more practical at harvesting) despite its prohibition according to the standard of treated wastewater reuse. Our study investigated the impact of different methods of irrigation: surface-drip, surface (flood), sprinkler, and subsurface-drip, on alfalfa quantity and quality using treated wastewater under semi-arid conditions. It concludes that subsurface-drip irrigation might be adapted as an efficient irrigation method under the above condition. Results also pointed to a high risk of pathogens using sprinkler and surface (flood) irrigation methods. Alfalfa productivity was among the lowest using sprinkler irrigation. Farmers might be switching to sprinkler use considering only the easiest management practices, mainly forage harvesting. Results of this study might be used and built on it to enhance the farmers' attitudes toward wastewater use and the impact of its application methods on sustainability.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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