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RESEARCH ARTICLE

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The effects of three techniques that change the wetting patterns over subsurface drip-irrigated potatoes

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Abstract

Wetting pattern enhancement is one of the goals of irrigation designers and researchers. In this study, we addressed three techniques (dual-lateral drip, intermittent flow and physical barrier methods) that change the wetting pattern of subsurface drip irrigation. To study their effect on the yield and water-use efficiency (WUE) of potatoes, field experiments were conducted for four seasons, during which the soil-water balance was continuously monitored using a set of capacitance probes. The results of the soil water patterns showed that both the dual-lateral and intermittent techniques increased lateral water movement and eliminated deep percolation, whereas the physical barrier had a limited effect on the top soil layer. The crop results indicated that the yield and WUE increased significantly in response to the application of the dual-lateral drip (up to 30%); the intermittent application also positively affected the yield (~10%) and the WUE (~14%), but these effects were not statistically significant according to the statistical model. The physical barrier showed a non-significant negative effect on the yield and WUE. These findings suggest the following recommended practices: the use of dual-lateral drip technique due to its beneficial results and its potential for increasing yields and reducing water consumption; the application of intermittent flow with more than three surges; and restricting the use of physical barriers to soils with high permeability.

Additional key words: intermittent application; subsurface drip irrigation; dual-lateral drip; physical barrier; water movement in the soil; *Solanum tuberosum* L.

Abbreviations used: CWT (consumed water per tuber); DM (dry matter); H (dual later technique); LSD (least significant difference); P (physical barrier technique); S (intermittent application technique); SC (starch content); SG (specific gravity); WC (water content); WUE (water-use efficiency).

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Introduction

The presence of water in the root zone is vital for plants, and its wetting pattern has a major impact on crop growth (Glenn, 2000; Raoof & Pilpayeh, 2013). The wetting pattern depends on two major factors: the soil properties and the irrigation application scheme. The soil properties include the texture, structure, and hydraulic conductivity, the existence of hardpan, the water table, and other variables (Pelletier & Tan, 1993); the irrigation application scheme includes the position of the equipment (on soil/in soil), the application rate and frequency, and the application method (drip/flood/sprinkler). In addition to the studies that have monitored the wetting pattern (*e.g.,* Souza & Matsura, 2003; Mirzaei *et al.*, 2009; Samadianfard *et al.*, 2012; Subbaiah, 2013), other studies have attempted to control or modify it. Phene *et al.* (1987) indicated that the wetted pattern around a buried emitter could be managed by regulating the irrigation frequency; these authors demonstrated that increasing the irrigation frequency with reduced volume per application draws the water toward the soil surface.

To control the downward movement of water, some studies have placed an impermeable barrier below the dripper lines. This barrier was made of polyethylene (Barth, 1995) or metal foil (Welsh *et al.*, 1995). In soils with extremely high infiltration rates, this physical barrier helps to retain water in the root zone, significantly increasing the crop yields compared to those in its absence in such a highly permeable soil (Elawady *et al.*, 2003; Awady *et al.*, 2008; Elnesr, 2012). This practice, additionally, helps to increase the water-use efficiency (WUE) by increasing the benefit from the applied water (Wang *et al.*, 2004). However, the physical barrier has some disadvantages, such as the need to excavate a deep wide trench to place the barrier, which is a labor intensive and costly. Additionally, if the physical barrier is installed at a shallow depth or in a soil with low permeability, severe problems may occur, including root rot and shallow root disease. Furthermore, potential hazards of salt accumulation and other toxicity problems are related to the accumulation of fertilizers and other chemicals (Elnesr *et al.*, 2014).

A different approach for adjusting the wetting pattern was introduced by Ismail *et al.* (2006). This method involves burying two dripper lines instead of one; the two lines are installed one below the other, and the two lines emit the same amount of water that is designed for the single dripper line. This method is based on the assumption that due to the higher-pressure head gradient, water moves faster into the dry soil than into the moist soil; thus, when the secondary drip line moistens the soil below the primary drip line, it causes water moves from the upper drip line to redistribute upward and laterally rather than moving downward. Therefore, these investigators called this technique “a hydraulic barrier.” This technique avoids almost all the physical barrier’s problems, as it requires no wider trenching than does normal lateral trenching. Through this technique, water applications may be adjusted between the upper and lower emitter lines depending on the root depth and root density, and more water may be applied through the upper emitter during the early growth stages when the plant roots are shallow. These results demonstrate that, when applied in the field, this technique increased the total and marketable yields of Jerusalem artichokes by 12 and 48%, respectively, clearly demonstrating the benefits of using such technique to increase crop yields under certain circumstances.

Furthermore, several studies have reported that applying water in an intermittent regime for flood irrigation improves water uniformity and increases crop yield (Monserrat *et al.*, 1993; Horst *et al.*, 2007). Subsequently, other investigators used the same concept for drip irrigation; calling this technique as intermittent, pulse, or surge drip irrigation (Vyrlas & Sakellariou, 2005; Elmaloglou & Diamantopoulos, 2008; Bakeer *et al.*, 2009; Eid *et al.*, 2013). This method improves the water distribution under subsurface drip irrigation by applying subsequent amounts of water to the soil, allowing water to redistribute before the next water application, which is assumed to accelerate lateral water movements. Several application regimes have been applied in the literature: according to specific ON and OFF times (Zin El-Abedin, 2006); according to a fixed number of ON times (Harmanto *et al.*, 2005; Bakeer *et al.*, 2009); and according to the applied water depth (New & Roberts, 2012).

The aims of this study were to investigate the effects of the intermittent flow (S), the dual-lateral drip system (H), and the physical barrier (P) on the crop growth and the wetting pattern, and to determine the extent to which these techniques affect potatoes (*Solanum tuberosum* L.) crop yield and water-use efficiency.

Material and methods

Field location and climate

The field study was carried out in Riyadh, Saudi Arabia, in the Educational farm of the King Saud University, 24°44’12.66”N and 46°37’13.32”E. The dimensions of the field were 32 m × 19 m (Fig. 1). The climate of the region is arid with very little precipitation through the year, except some flash rains in March and April. In summer months, the temperatures are extremely hot, while in winter, the temperatures are mild with some few winds and sand storms. Monthly averages of the temperature, relative humidity, rainfall, and wind speed are shown in Table 1.

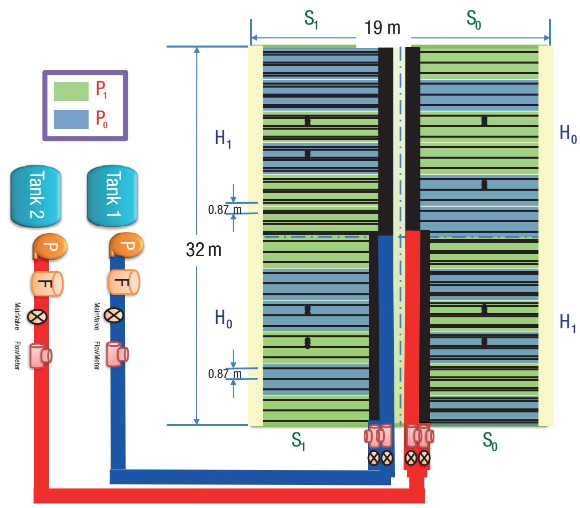

Figure 1. Field layout of the experiment.

Soil properties

The soil of this field was sandy loam to a 60 cm depth, with average contents of 71.1% sand and 12.7% clay. The field capacity was 0.192; the permanent wilt-

Table 1. Climatic data of the study area (yearly averages 1985-2011)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$T_{max,}$ °C	20.2	23.3	27.7	33.3	39.5	42.6	43.7	43.7	40.6	35.5	27.9	22.2
T_{avg}, °C	13.4	16.3	20.5	26.0	31.9	34.7	35.8	35.7	32.4	27.3	20.5	15.3
T_{min}, °C	6.9	9.2	13.2	18.3	23.4	25.2	26.4	26.3	22.8	18.2	13.0	8.7
RH_{max}, %	69.9	57.9	52.7	50.0	31.1	18.1	17.5	21.3	24.3	34.6	54.1	70.3
RH_{avg}, %	48.8	38.0	33.3	30.1	18.0	10.7	10.7	12.8	14.6	21.3	37.2	49.6
RH_{min}, %	30.3	22.3	18.4	15.7	9.5	5.9	6.2	7.2	8.1	11.9	23.1	31.2
RF_{sum}, mm	15.5	9.6	21.7	26.6	6.3	0.0	0.0	0.0	0.0	1.2	12.7	17.3
WS_{max}, m/s	7.7	7.7	10.3	7.2	8.2	21.6	9.8	10.8	5.7	7.7	8.2	14.4
WS_{avg}, m/s	2.8	3.2	3.4	3.4	3.2	3.4	3.5	2.9	2.3	2.0	2.3	2.6
ETo_{avg}, mm/d	5.2	6.6	8.4	10.8	14.1	16.6	17.4	16.1	13.3	10.1	7.3	5.5

T: temperature, RH: relative humidity, RF: rainfall, WS: wind speed, ETo: reference evapotranspiration, max: maximum, min: minimum, avg: average. Data from the Presidency of Meteorology & Environment Protection, Riyadh, Saudi Arabia.

ing point was 0.059; the pH and electrical conductivity were 7.48 and 3.1 dS/m, respectively; and the organic matter was <0.15% in all of the layers. The saturated hydraulic conductivity was 1.06 m/d.

Experimental design

Three techniques were studied (physical barrier, dual-lateral drip and intermittent application −surge drip−), each at two levels: applied and not applied (P_1 and P_0, H_1 and H_0, S_1 and S_0, respectively). The experimental design was factorial 2^3, with 8 treatments in total, including interactions. Due to the nature of the treatments and the difficulty of conducting randomization for complete randomized design models, the selected statistical model was split-split plot design, with the intermittent application as whole plots, the dual-lateral drip as the subplots and the physical barrier as the sub-subplots. Each treatment was applied on nine individual rows (replicates). The experiments were repeated for four open-field seasons: Sept 2011, Feb 2012, Sept 2012, and Feb 2013.

Irrigation network design

For all of the plots in the subsurface drip network, the following parameters were applied: the main lateral line was buried 15 cm below soil surface as commonly recommended by commercial potatoes growers. The laterals were equipped with 4 L/h built-in emitters, 33 cm apart. When the dual-lateral technique was applied, an additional lateral line was buried 10 cm below the main lateral line (25 cm below the soil surface) as recommended by Ismail *et al.* (2006). The scheduled amount of water was divided equally between the two laterals. For the intermittent flow, the scheduled water was split into equal amounts according to the selected surge rate, 3 surges, as suggested by Du Plessis (2004), where the OFF duration was selected three times the ON duration to increase the water redistribution time. For example, if the desired water amount is 12 mm/d and the surge rate=three, the system should work three times, each time applying 4 mm/d. The physical barrier was placed 30 cm below the soil surface as an intermediate depth within the root zone. The used barrier was in the form of a semicircular PVC arc with a 110 mm width; this width is narrower than the physical barrier of Ismail *et al.* (2006) (50 cm width) but is reasonable compared to the size of Brown *et al.* (1996), which was less than an 8 cm L-shaped strip. The amount of water applied to all of the plots was the same; the irrigation process was scheduled by calculating the crop evapotranspiration according to the method of Allen *et al.* (1998) and based on our field meteorological station historical and daily data. According to the numbers of emitters in each plot, the desired amount of water was converted to the equivalent operation time and then fed to modular controllers Rainbird ESP (Rainbird Corp., USA) weekly to control the irrigation process automatically.

Soil-water monitoring

To monitor the water movement in the soil, we installed capacitance probes that monitor the water movement continuously, EnviroSCAN (Sentek, Australia) with 5 sensors each. For each treatment, we installed two probes: one bordering the emitters' line (Fig. 2) and the other 20 cm away (center to center). An additional access tube was installed 25 cm from the second tube for on-demand measurements using another capacitance probe, Diviner 2000 (Sentek, Australia). The access tube locations are shown in Fig. 1. Each probe consists of 5 sensors installed at 10, 20, 30, 40, and 60 cm depths. The data were collected manually every 3-5 weeks and then analyzed by the IrriMAX 8.0 software. A rigorous calibration process was performed according to the manufacturer's manual as described in Elnesr *et al.* (2013a), and the readings were logged every 30 min throughout the experiment.

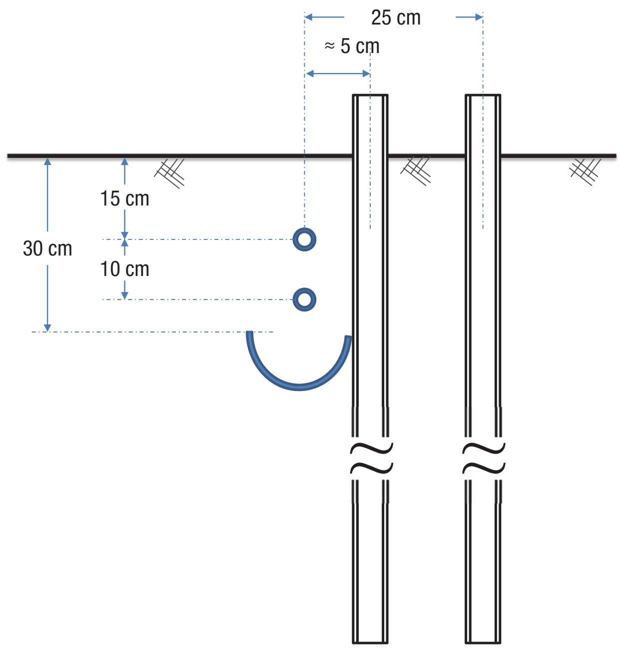

Figure 2. Schematic diagram showing the dimensions of the system components (if any exists).

Potatoes planting

We selected a variety of potatoes that is suitable for our environment. This variety is called Hermes (Hermes DDR 5158 × SW 163/55), a product of the NIVAP Company from The Netherlands (NIVAP, 2011). The planting distance was 50 cm within a row and 85 cm between rows. All of the necessary fertilization and protection applications were performed uniformly on all the treatments.

Pre- and post-harvest measures

From the 8th-10th week of cultivation, a representative sample plant was taken from each crop row to evaluate the growth indicators; we measured its length and weighed each of its parts separately (leaves, shoots and tubers, if any). Approximately 100 g of each part was weighed and then dried in a 70°C oven for 3-5 days (until no weight loss occurred between two subsequent weighings); finally, the water content (WC) percentage was calculated as:

$$WC\ (\%) = (Initial\ Weight - Dry\ Weight) / Dry\ Weight \cdot 100.$$

After ~120 days of cultivation, the crop was harvested. At harvest, the crop rows were weighed individually (72 crop rows), and the tubers of each row were weighed, counted, and assigned to four groups according to size (represented as least diameter): >7.5 cm, >5.0 cm, >2.5 cm, and <2.5 cm. According to the local market, only the first two groups are considered marketable. Subsequently, three random fruits from each row were selected; portions of the fruits were sliced and dried at 70°C for 72 h to measure the dry matter and WCs. The dry matter of potatoes, their specific gravity, and their starch content were evaluated using the methods of Haase (2004) as follows: 3 sample tubers were randomly collected from each row, the samples were cleaned with tap water, and the weight of wet potato tubers in water was measured with a precision balance SB-8000 (Mettler-Toledo, Switzerland). To obtain the weight of 5050 g of wet tubers, a correction was made according to EC (1999), as shown in Eq. [1]:

$$W_{uw} = \frac{5050 \times W_w}{W_a} \qquad [1]$$

where *Wuw* is the underwater weight, *Ww* is the balance reading while the tubers were in water (weight in water), and *Wa* is the weight in air.

The specific gravity (SG) was calculated as follows:

$$SG = \frac{W_a}{W_a - W_w} \qquad [2]$$

The starch fresh weight percentage (*Sf*) was calculated as follows:

$$S_f = \begin{cases} -1.116 + 0.044 \times W_{uw} & \cdots 13 - 23\% starch \\ -1.014 + 0.044 \times W_{uw} & \cdots \geq 23\% starch \end{cases} \qquad [3]$$

The percent of dry matter in the tubers (DM) was calculated as follows:

$$DM = \begin{cases} 0.417 + 0.052 \times W_{uw} & \cdots 13 - 23\% starch \\ 0.785 + 0.052 \times W_{uw} & \cdots \geq 23\% starch \end{cases} \qquad [4]$$

Another method to determine the dry matter is the method of Maerker (Niessen, 1955):

$$\textit{Dry matter } (\%) = 214 \; (\textit{specific gravity of tubers} - 0.988).$$

One of the most important indicators characterizing the irrigation process is the WUE (kg/m^3), which is defined as the ratio of the crop yield to the applied water and can be expressed as in Eq. [5]. Additionally, the amount of consumed water per tuber (CWT, L/tuber) were calculated according to Allan (1998), as in Eq. [6]. The estimated values of CWT for the potatoes and the methods of determination were obtained from Mekonnen & Hoekstra (2011).

$$WUE = \frac{1}{n}\sum_{r=1}^{n}\frac{Y_r}{WC_r} \qquad [5]$$

$$CWT = \frac{1000}{n}\sum_{r=1}^{n}\frac{WC_r}{FC_r} \qquad [6]$$

where n is number of replicates (rows) per treatment, r is the counter, Yr is the yield of the row (kg), WCr is the water consumption of the row (m^3/row), and FCr is the fruit count per replicate, the factor 1000 is a conversion factor from cubic metres to liters.

Statistical analysis

Data were subjected to analyses of variances (ANOVA) according to a factorial split-split plot design. Means were tested with Fisher's least significant difference method (p<0.05). All the statistical analyses were undertaken using the Statistix package v7.0 (Analytical Software).

Results and discussion

Soil water patterns

To understand the nature of the applied treatments, the WCs were tracked for two years using fixed capacitance probes as mentioned in the materials and methods section above. Figure 3 presents the average WC values for each of the applied treatments in 8 charts; each chart shows the average seasonal readings for two probes: one was installed near the emitter line (5 cm away), and the other was installed far from the line (25 cm away). In each chart, the results of each probe are shown in the same color; blue and red represent the 5 cm and 25 cm probes, respectively. Each probe family-line chart represents the logs of the four successive seasons in lightweight lines, whereas the overall average line is thicker. Although the soil of the field is almost homogeneous, it has spatial variability due to the natural components of small rocks and organic matter, among other reasons. Therefore, these charts may reflect not only the treatment's effect, but the soil may also influence some data points. In the chart and the following discussion, each treatment will be abbreviated to three characters representing the existence/absence of the treatment: when the treatment is applied, the symbol S, H, or P was placed in sequence, whereas when it is not applied, we insert a zero instead. For example, $S_1H_0P_0$, will be abbreviated to S00, and $S_0H_1P_1$ will be abbreviated to 0HP.

In all of the water patterns in Fig. 3, the WC at the 60 cm depth was the greatest except for in the control treatment (000) and the combined treatment (S0P), which may be due to the differences in the soil type, as the soil was sandy loam in the top 60 cm and was solid rock below, which may blockade water from being drained. The differences in the two treatments may be due to the absence of rocks at these locations.

The WC pattern at a 5 cm distance in the control treatment (000) reflected a bump at a 30 cm depth where the WC=23%, whereas the overall WC at all of the depths was ~17.5%. This increase in the WC at 30 cm may reflect water accumulation in the root zone due to excess flux from the emitter, as the entire volume of water was applied at once, unlike with the S or H treatments, in which the water flux was split either by time or by location, respectively. A similar effect occurred in the 00P treatment, where the WC increased at the 30 cm depth, but the effect of the physical barrier led to water accumulation at the 40 and 60 cm depths (the applied barrier is narrow and holds only a certain amount of water, allowing water to escape around it), making the line appear to be almost straight, with a negative slope from the 20 cm to 60 cm depth. Pulsating water through the buried emitters allows the WC to reach its maximum values in the root zone, as seen in chart S00 in Fig. 3, which might be attributable to the redistribution that occurred between surges, permitting the lateral movement of water up to 24% at a 25 cm distance (the red curve) and up to 28% at a 5 cm distance (the blue curve). This result agrees with that of Vyrlas & Sakellariou (2005), who found that intermittent application in both surface and subsurface plots produced wider wetted patterns. In contrast, it was found in this study that the dual-lateral system (chart 0H0, Fig. 3) allowed more lateral movement in the top 30 cm, as the WC at a 25 cm distance was greater than its values at a 5 cm distance, agreeing with the results of Ismail *et al.* (2006), who called the dual-lateral system 'the hydraulic barrier' because they

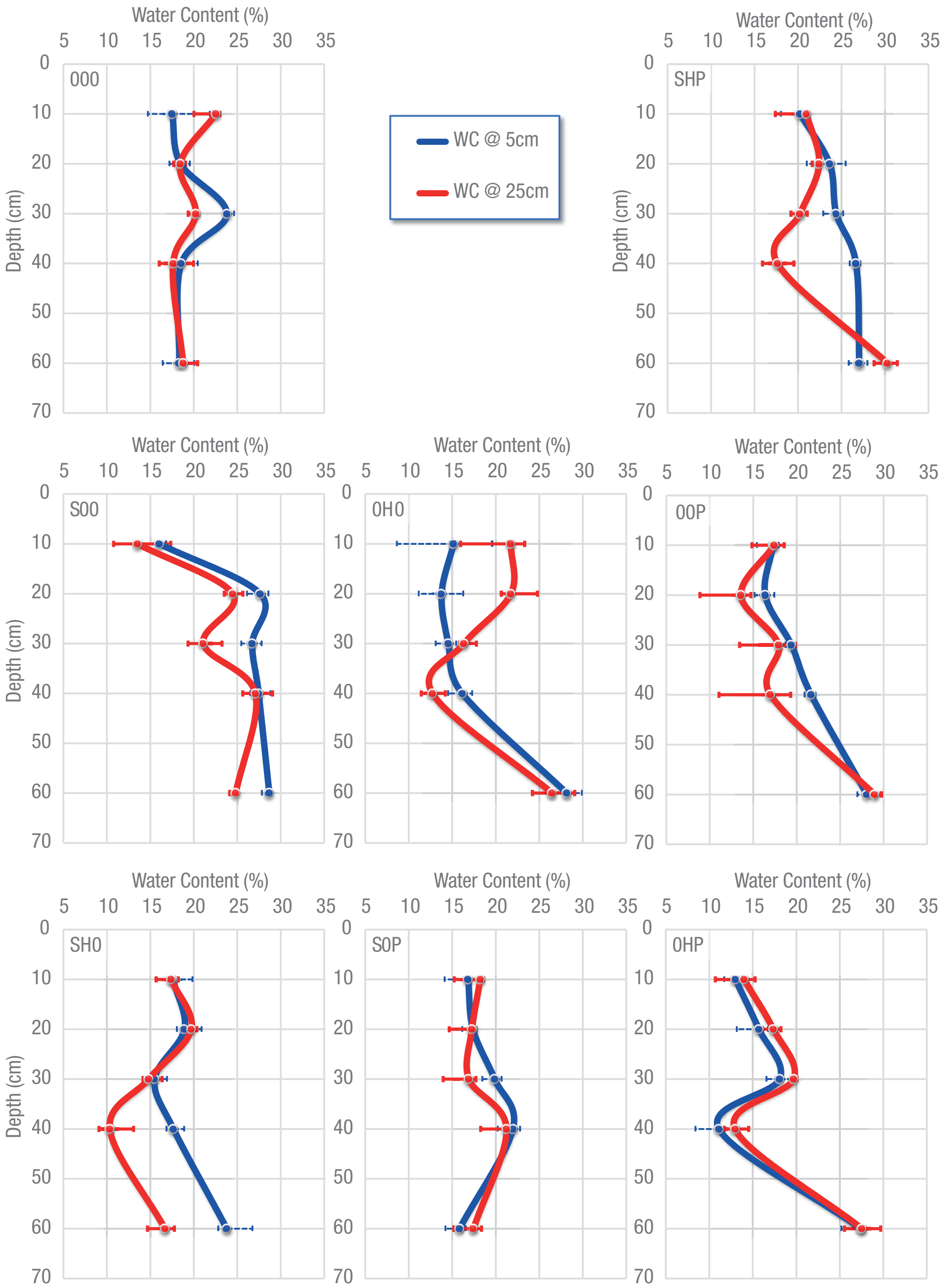

Figure 3. Soil water content (WC) at 5 and 25 cm perpendicular distances from the buried emitter(s).

found that the lower lateral may act as a hydraulic barrier forcing the water to spread laterally, similar to the effect of the physical barrier. However, in their simulation study, Elnesr *et al*. (2013b, 2014) concluded that the dual-lateral technique is not a hydraulic barrier but, instead, only modifies the wetting pattern and may substantially enhance the solute transport under certain conditions. However, in the present study, it was found that the dual-lateral technique significantly increased the crop yield and WUE, enhancing the lateral water movement; this increase in the lateral movement may be the reason for such an increase in the crop yield. Additionally, the combined S and H treatment (SH0) showed the combined effects of the two treatments. The 25 cm curve (the red) was less than the 5 cm curve in the S00 treatment, and the situation was reversed in the 0H0 treatment; the combined treatment SH0 coincides with the two curves, reflecting the uniformity of the WC between 5 and 25 cm laterally and between 10 and 30 cm deep in the soil. The combined treatment between H and P (chart 0HP, Fig. 3) also reflects the effect of each of the treatments; the physical barrier blocked off the water from moving downward in the 40 cm layer, similarly to the effect shown in the 00P chart at the 25 cm line, whereas the effect of the dual-lateral line appears in the increase of the WC values at the 25 cm line over the 5 cm line. Nevertheless, the S0P chart shows the least deep percolation of all the treatments because both the physical barrier and the intermittent treatments exist. This appears to agree with Kenig *et al*. (1995), who concluded that the pulsating drip reduces deep percolation in addition to the physical barrier, whose main role is to prevent such percolation. Finally, the results demonstrate that the combined effect of the three treatments results in the maximum WC value at 5 cm at every point (10, 20, 30, and 40 cm), whereas the 25 cm line matched the 5 cm curve only in the top 20 cm, after which the former showed water shortages in the 30- and 40-cm layers. This variation between the two lines demonstrates that the triple combination among treatments increased the WC only near the emitter but did not force water to spread laterally as in the 0H0 treatment except for in the top 20 cm, which may be attributed to the crop yield and size results that demonstrated the superiority of the 0H0 treatment over the SHP treatment combination.

Potato yield

The statistical analysis for the yield shows that the effect of the dual-lateral technique (H) was highly significant (p=0.031): the overall average of the H_1 was 24.35 t/ha and was 19.2 t/ha for H_0 (LSD=4.50 t/ha). This positive effect (~27% increase on average) was evident for all of the seasons, especially in the first two seasons (Fig. 4H). The yield effect for the third and fourth seasons was not observed as in the first two seasons, this might be attributed to the effect of soil compaction, as the soil was not tilled in the second year prior to cultivation. The overall significant increase in the potato yield agrees with some of the results reported by Ismail *et al*. (2006), who applied the dual-lateral technique, where the technique led to a 33% decrease in tomato yield and a 47% increase in the marketable Jerusalem artichoke (*Helianthus tuberosus* L.) tubers. The negative effect on tomatoes that was reported by Ismail *et al.* (2006) could be attributed to the setup of their experiment, as they applied the dual-lateral technique with variable distances between the two laterals and variable gaps (varied between 10 cm and 40 cm); however, these authors reported that the larger gaps exceeding 10 cm produced a low tomato yield due to a lack of water, as their soil had a very high infiltration rate. However, the tubers of the Jerusalem artichokes, which are similar to the tubers of potatoes, reflected an increase in the yield.

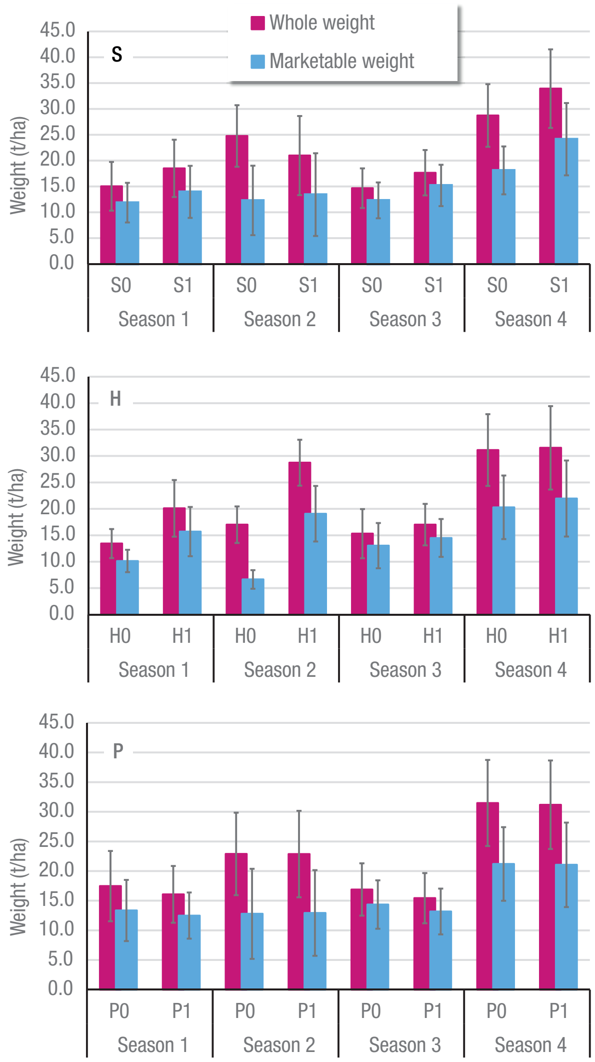

Figure 4. The effect of the three techniques on the yield of potatoes during four seasons. Bars indicate standard errors (n=9).

The intermittent (surge) flow showed a good effect on the potato yield in all of the seasons except the second season (Fig. 4S); however, this effect was not statistically significant (p=0.39), as the intermittent treatments were considered whole plots in the split plot experimental design. The overall average yield of the treatment was 22.7 and 20.8 t/ha for S_1 and S_0, respectively (LSD=6.3), indicating that this technique has a positive effect on potatoes, which agrees with other investigators (Bakeer *et al.*, 2009; Abdelraouf *et al.*, 2013; Eid *et al.*, 2013), who reported an increase in potato yield by using pulsating drip irrigation; however, the results of this research were not significant as those of the previous works, which may be attributable to the smaller number of surges in the current research compared to the number of surges in the cited works.

The physical barrier showed a negative non-significant (p=0.16) effect on the yield; the average yield was 22.18 and 21.39 t/ha for P_0 and P_1, respectively (LSD=1.11 t/ha). Although this treatment had the lowest LSD value due to its position in the statistical analysis as a sub-subplot, it showed no significance, confirming that it has no effect on the yield under these experimental conditions. The season comparison (Fig. 4P) shows that the presence of the physical barrier had a negative effect during the winter seasons (1 and 3), whereas it had no effect during the summer seasons (2 and 4), which may be attributable to the occurrence of rainfall (in March and April, Table 1) in addition to the irrigation, which may have led to an excess of water in the root zone, which is not optimal for potato tubers. This result disagrees with the results of Ismail *et al.* (2006), who reported a large increase in the yield of tomatoes and Jerusalem artichokes when applying the physical barrier (119 and 138%, respectively). However, the contrasting results between this study and the study of Ismail *et al.* (2006) may be attributed to the soil type. Their study took place in Sinai-Egypt on a sandy soil with a very high infiltration rate (0.667 m/h) and a hydraulic conductivity of 24.6 m/d, whereas the current study's soil texture is sandy loam with a hydraulic conductivity of 1.06 m/d. The high rate of infiltration allows water to escape rapidly from the root zone; therefore, the physical barrier is useful for preventing the unwanted downward infiltration of the water, containing it within the root zone as long as the plant can benefit from it. However, the medium-textured soil does not require such barrier, as the required amount of water is already retained in the root zone; thus, the side effects of the physical barrier would appear to be the growth inhibition of the roots and the retention of harmful chemicals, prohibiting their dispersal by free drainage, as reported by Elnesr *et al.* (2014). This result led to recommend usage of the physical barrier only in soils with high infiltration rates.

To study the individual effect of each treatment combination on potato yield, we listed the eight possible interactions of the three treatments (two levels each) in Table 2. In almost every season, the maximum yields were achieved in the S_1H_1 treatment combination, and the smallest yields were achieved in the S_0H_0 treatment combination. Nevertheless, statistically, the yield of the combined treatments S_1H_1 was significantly different from that of the other treatments, followed by S_1H_0 and then S_0H_1, as detailed in Table 3. This result confirms that the interaction of the intermittent and dual-lateral treatments has a good effect on the crop yield. The hot season yield (2nd and 4th) was higher than that of the cold seasons (1st and 3rd); however, this result was unexpected, as potatoes are recommended to be cultivated from the 1st to the 15th of September in the Riyadh region, and we attempted to cultivate them in February (in addition to September) to increase the number of seasons during the allowed project duration. The success of the potatoes cultivation in this new planting period is a benefit for potato-growers in the region.

In addition to the yield, another important marketing consideration is the tubers average weight (Table 3); the largest tuber weight was achieved with the S_1H_1 treatments regardless of the existence or absence of the P treatment, but the absence of a physical barrier resulted in a higher weight of ~0.14 kg/tuber, which is significantly different from all other treatments. Regarding the marketable yield, the statistics showed that only the H treatment was significant, with 18.24 and 12.53 t/ha, respectively, for H_1 and H_0 (LSD=4.22, p=0.016); however, although the S treatment was not statistically significant at p=0.05, it was very close to significance (p=0.054), and the values of S_1 and S_0 were 17.12 and 13.65 t/ha, respectively. These results demonstrate that these two treatments enhance both the quality and quantity of the yield.

Additionally, the average number of tubers per row was not statistically significant for any of the treatments (total yield); however, for the marketable yield, the statistical analysis (Table 3) demonstrated that the S_1H_1 treatments produced a significantly higher number of tubers than that of the other treatments, with ~$227{\cdot}10^3$ tuber/ha on average, whereas the control treatment $S_0H_0P_0$ produced $183.1{\cdot}10^3$ tubers/ha. The next significance level was the S_0H_1 treatment combination, with $200.2{\cdot}10^3$ tuber/ha. The H and S treatments exhibited significant effects on the number of potato tubers (Table 3), where the averages of the H treatments were $213.8{\cdot}10^3$ and $197.3{\cdot}10^3$ tuber/ha for H_1 and H_0, respectively, and the averages of the S treatment were $211.2{\cdot}10^3$ and $199.9{\cdot}10^3$ tuber/ha for S_1 and S_0, respectively. This result, along with the total yield results, clarifies the positive effect of the dual-lateral and the intermittent flow techniques on the yield of the potatoes.

Water-use efficiency

As explained above, the same amount of water was applied to each of the studied treatments depending on the calculated crop water requirements; however, for several reasons, the actual amounts of water that were applied to the different plots varied to some extent. The reasons for this variation include differences in the pressure heads at the time of application, variation in the emitters, timing errors, automatic valve malfunctions, and other factors. Although such

Table 2. Potato yield during four seasons showing the results for each of the applied treatment combinations. Numbers in (round) and [square] brackets are the maximum and minimum values in each season, respectively

	S	H	P	Gross yield (t/ha)	Marketable yield (t/ha)	Tubers count (×1000/ha)	Average tuber's weight (g)
Season 1	S_0	H_0	P_0	12.1	9.7	105.6	111.3
			P_1	[11.6]	[9.4]	[96.4]	(114.0)
		H_1	P_0	18.5	14.0	171.7	98.6
			P_1	18.0	14.4	169.1	101.7
	S_1	H_0	P_0	14.3	9.9	191.1	[70.9]
			P_1	15.8	11.5	194.3	77.3
		H_1	P_0	(25.0)	(19.8)	(225.7)	103.1
			P_1	18.9	14.7	208.7	89.6
Season 2	S_0	H_0	P_0	19.7	6.7	228.3	68.0
			P_1	19.5	6.9	(394.5)	[55.4]
		H_1	P_0	29.0	15.8	240.4	91.0
			P_1	(30.8)	19.8	279.6	(95.5)
	S_1	H_0	P_0	[14.3]	[6.4]	[212.2]	61.7
			P_1	14.5	6.6	232.2	58.9
		H_1	P_0	28.5	(22.2)	331.0	85.4
			P_1	26.7	18.4	306.3	82.5
Season 3	S_0	H_0	P_0	15.6	13.1	95.9	153.5
			P_1	[13.8]	[11.6]	[80.8]	159.1
		H_1	P_0	14.9	12.4	97.6	[143.5]
			P_1	14.4	12.2	88.9	152.4
	S_1	H_0	P_0	17.5	15.2	85.7	(188.5)
			P_1	14.3	12.2	76.3	173.6
		H_1	P_0	(19.5)	(16.7)	(102.1)	178.1
			P_1	19.2	16.7	98.6	184.5
Season 4	S_0	H_0	P_0	29.7	18.5	(302.7)	91.2
			P_1	28.0	[16.9]	292.7	[88.8]
		H_1	P_0	30.8	19.7	299.2	96.3
			P_1	[26.4]	17.2	255.5	95.9
	S_1	H_0	P_0	35.0	24.7	272.5	115.6
			P_1	31.7	21.0	295.7	97.7
		H_1	P_0	30.4	21.8	[245.0]	110.0
			P_1	(38.7)	(29.0)	300.8	(120.1)
Overall averages	S_0	H_0	P_0	19.3	12.0	[183.1]	106.0
			P_1	[18.2]	[11.2]	216.1	[104.3]
		H_1	P_0	23.3	15.5	202.2	107.3
			P_1	22.4	15.9	198.3	111.4
	S_1	H_0	P_0	20.3	14.0	190.4	109.2
			P_1	19.0	12.8	199.6	101.9
		H_1	P_0	25.8	(21.9)	226.0	119.2
			P_1	(25.9)	19.7	(228.6)	(119.2)

errors were rare, the water meters were checked daily to correct any variations in the water amounts as quickly as possible. The statistical analysis demonstrated (Table 3) that only the H treatment had a significant effect on the WUE (p=0.015), with 3.60 kg/m^3 for H_1 and 2.78 for H_0 ($LSD_{0.05}$=0.59), confirming that the dual-lateral system is very effective in conserving water as well as in increasing crop yields.

Table 3. Statistical results of the overall averages (total and M=marketable)

Treat-ments	Yield (t/ha)		Water use (kg/m³)		No. tubers (×1000 tubers/ha)		Water consumption (L/tuber)		Water content in plant (%)			Avg. tuber weight (kg)	
	Total	M	Total	M	Total	M	Total	M	Leaves	Shoots	Tubers	Total	M
$S_1H_1P_1$	25.88 a	19.71 a	3.79 a	3.08 a	228.61 a	118.37 a	33.45 c	60.89 f	82.35 ab	83.71 cd	78.16 b	0.12 ab	0.178 b
$S_1H_1P_0$	25.84 a	21.88 a	4.13 a	3.52 a	225.96 a	119.46 a	33.44 c	62.15 f	82.03 b	81.99 e	79.36 a	0.14 a	0.207 a
$S_1H_0P_1$	19.05 d	12.85 cde	2.78 cd	2.05 c	199.63 ab	77.78 cd	40.78 ab	90.70 bc	82.33 ab	84.92 ab	79.20 a	0.10 b	0.166 b
$S_1H_0P_0$	20.30 cd	14.04 bcd	2.94 bcd	2.24 bc	190.38 ab	80.07 c	38.64 abc	86.57 cd	82.80 a	85.11 a	79.24 a	0.11 b	0.173 b
$S_0H_1P_1$	22.39 bc	15.89 b	3.27 b	2.58 b	198.26 ab	92.05 b	38.32 abc	77.13 de	82.94 a	83.94 bcd	78.45 ab	0.11 b	0.182 ab
$S_0H_1P_0$	23.30 b	15.48 bc	3.23 bc	2.51 b	202.21 ab	93.36 b	37.22 bc	74.04 e	82.54 ab	83.26 d	78.73 ab	0.11 b	0.170 b
$S_0H_0P_1$	18.23 d	11.20 e	2.66 d	1.84 c	216.09 ab	63.29 e	43.63 a	104.94 a	82.80 a	84.63 abc	78.48 ab	0.10 b	0.180 b
$S_0H_0P_0$	19.28 d	12.03 de	2.76 cd	1.97 c	183.11 b	66.70 de	42.53 ab	98.71 ab	82.86 a	84.21 abcd	79.00 ab	0.11 b	0.179 b
$LSD_{0.05}$	2.22	2.67	0.474	0.60	39.21	11.89	7.06	11.56	0.758	1.061	1.017	0.0207	0.026
SE	1.13	1.36	0.241	0.30	19.91	6.04	3.58	5.871	0.385	0.539	0.516	0.0105	0.013
Summary of S-H interaction													
S_1H_1	25.86	20.79	3.96	3.30	227.29	118.92	33.44	61.52	82.19	82.85	78.76	0.13	0.193
S_1H_0	19.67	13.44	2.86	2.15	195.01	78.92	39.71	88.64	82.57	85.02	79.22	0.11	0.170
S_0H_1	22.84	15.68	3.25	2.55	200.24	92.70	37.77	75.58	82.74	83.60	78.59	0.11	0.176
S_0H_0	18.76	11.61	2.71	1.91	199.60	65.00	43.08	101.83	82.83	84.42	78.74	0.11	0.180
Summary of individual effects of S and H													
S_1	22.77	17.12	3.41	2.72	211.15	98.92	36.58	75.08	82.38	83.94	78.99	0.12	0.181
S_0	20.80	13.65	2.98	2.23	199.92	78.85	40.43	88.71	82.79	84.01	78.66	0.11	0.178
H_1	24.35	18.24	3.60	2.93	213.76	105.81	35.61	68.55	82.47	83.23	78.67	0.12	0.184
H_0	19.22	12.53	2.78	2.03	197.30	71.96	41.40	95.23	82.70	84.72	78.98	0.11	0.175

Means with same letters are not significantly different from each other at p=0.05.

However, none of the treatments/treatment-combinations showed a significant difference; however, when comparing means, we found that the WUE of S_1 was better than that of S_0 (3.41 and 2.98 kg/m^3 respectively, $LSD_{0.05}$=0.62, this difference being not statistically significant). For the P treatment, the WUE for P_0 and P_1 were 3.26 and 3.12, respectively, and the $LSD_{0.05}$=0.23, also not statistically significant. Nevertheless, the highest WUE value (4.13 kg/m^3) was for $S_1H_1P_0$ (Table 3), and the lowest WUE value was achieved in the treatment $S_0H_0P_1$, which is the opposite of the treatment combination with the maximum WUE; however, the WUE values of applying $S_1H_1P_1$ or $S_1H_1P_0$ were significantly different from those of all the other treatment combinations. This result demonstrates that the division of the water amount (under the dual-lateral system) and the division of the irrigation time (under intermittent application) are successful practices for increasing potato yield and for conserving water, thereby increasing the WUE.

Other physiological measures

In addition to the yield and water consumption, the tuber dry matter (DM), specific gravity (SG) and starch content (SC) as well as the WC of the tubers, leaves and stems were evaluated. No significant differences were found due to any treatment on DM, SG, or SC; therefore, the contents of the tubers were not affected by any of the treatments in this study. However, the WC of the tubers was slightly affected by the physical barrier, as the average WC of the tubers was 79.1% and 78.5% for P_0 and P_1, respectively, and the $LSD_{0.05}$=0.5%. Although the differences were small, they were statistically significant according to the experimental design. However, this result shows that the tuber WC decreased in the presence of the physical barrier; this may be interpreted as the physical barrier forces the water to flow laterally, leading to less water in the tuber zone, whereas in the absence of the physical barrier, water does not percolate downward due to the medium soil texture. Therefore, the benefit of the physical barrier disappears, and the barrier becomes a drawback that decreases the amount of water in the tuber zone instead of increasing it; this decrease in the soil WC is reflected by a decrease in the tuber WC previously reported (Levy, 1986; King *et al.*, 2003). Moreover, it was found that both the physical barrier and the dual-lateral techniques affect the WC in the plant shoots, as the existence of any of these techniques decreases the WC in shoots by ~1.5% (WC was 84.7% and 83.2% for H_0 and H_1, respectively, and 84.3% and 83.6% for P_1 and P_0, respectively). When applying the dual-lateral treatment, the water requirement was split into two equal amounts between two lateral lines, one at a 15 cm and the other at 25 cm depth. In contrast, in the single lateral treatments, the entire volume of water was applied through one lateral line at a 15 cm depth; therefore, the total volume of applied water at the 15 cm depth was larger in the single lateral treatments (H_0), which may be the reason that the shoots were wetter in the H_0 than in the H_1 treatments.

In summary, we studied the effects of three techniques that lead to different wetting patterns. The soil-water measurements in this study demonstrated that the dual-lateral drip system and the intermittent application increased the lateral water movement, producing wider wetting patterns that influenced the crop yield, whereas the physical barrier had a limited effect on the 10-30 cm layers. The crop results demonstrated that the dual-lateral drip technique significantly increased the yield and the water-use efficiency of potatoes during the four cultivated seasons, while both the intermittent application and the physical barrier were not statistically significant. The use of the dual drip technique is recommended due to its good results; however, more research is needed for the sequential operation of the two laterals, the usage of different quality waters in each lateral, and for the intermittent application with different rates, especially higher rates and with different soil types. Additionally, the physical barrier is not recommended for use except in highly permeable soils, where there is a problem keeping the water in the root zone, as the effect of the barrier becomes negative if installed in medium- or heavy-textured soils.

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