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Modified Surface Drip Irrigation and Hydraulic Barrier Impacts on Soil Moisture and Water Productivity for Tomatoes in a Greenhouse

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Abstract: Considerable amounts of irrigation water of vegetable crops grown in homogenous sandy soil profiles could be subjected to deep percolation water losses due to inappropriately designed surface or subsurface drip irrigation methods. This study aimed to investigate the combined influence of implementing clay soil layer in homogenous sandy soil profile of low-tech greenhouse ridges and using modified surface drip irrigation (M-DI) on soil moisture distribution and water productivity of tomatoes. In the greenhouse, a 7.5 cm thick clay soil layer was implemented 15 cm from the soil surface of each ridge as a hydraulic barrier. Three irrigation regimes (100%, 70% and 50% of ETo) were imposed with the M-DI on tomato plants and 100%ETo with surface drip irrigation (DI) as control. Regarding economic valuation, viability was preserved for the M-DI and DI methods. The outcome indicated that soil moisture spreads more horizontally than vertically on the sandy soil above the clay soil layer. The combined effect of the homogenous sandy soil profile amendment and full irrigation (100%ETo) with the M-DI irrigation method increased the tomato fruit yield by 64.5%. Furthermore, the combined influence enhanced water productivity by the M-DI to 54.7 kg/m^3 compared to 32 kg/m^3 by the DI. However, M-DI demonstrated dominance over DI regarding returns, yield, and profit. Economic-wise, the M-DI requires 50% less of the lateral pipelines needed by the DI in low-tech greenhouses. Adopting the M-DI with a hydraulic barrier can improve soil moisture, water productivity, yield, and returns for tomato crops in low-tech greenhouses under sandy soil conditions. Also, the M-DI with the hydraulic clay barriers was an economically viable investment compared to the DI without clay barriers for growing tomatoes in low-tech greenhouses.

Keywords: low-tech greenhouse; homogenous sandy soil profile; modified surface drip irrigation; hydraulic barrier; irrigation regimes; soil moisture; water productivity

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1. Introduction

The Kingdom of Saudi Arabia (KSA), like other arid and semi-arid regions of the globe, has agricultural production dependent on vulnerable water resources [1]. Due to climate change and global warming, water insecurity is expected to be exacerbated in the near future. The KSA has deficient annual rainfall and lacks perineal rivers and streams. In addition, soil profiles of most indoor and outdoor farming production are dominated by non-fertile coarse-textured sandy soils [2]. Therefore, due to the low water holding capacity of 8% and high-saturated hydraulic conductivity (23.75 cm/h) of the coarse-textured sandy soils, a significant amount of irrigation water in the greenhouse drain is subjected to deep percolation beyond the root zone [3–5]. These coarse-textured sandy soils homogenously existed in the kingdom at more than 100 cm depth in the greenhouse soil profiles. Such an environment of greenhouses results in low water use efficiency and loss of fertilizers [6,7]. Accordingly, high inputs are required for vegetable production when sandy soils of more than 80% sand and less than 10% clay exist in soil profiles of 100 cm depth [8]. This is because such sandy soils have poor physical and chemical properties.

A survey indicated that the total number of greenhouses in the KSA was 73,547, with a total area of 32.95 million square meters, of which more than 38.3% was produced by tomato crops [9]. Indoor farming in the KSA is considered the best way to enhance the utilization of scarce water resources more efficiently and alleviate the challenges of the agricultural sector's freshwater shortage. Also, indoor farming produces more good quality vegetables economically than outdoor farming [10,11]. The water use efficiency (WUE) of a crop grown in the greenhouse was five times more than that of an open field [11].

Surface drip irrigation is an innovative water-saving technology used in agriculture to replace sprinkler and flood irrigation methods. During the 1980s, it was introduced commercially to the KSA [12]. It has the potential to efficiently apply scarce water resources for greenhouse vegetable crops compared to furrow irrigation [4,13]. However, the DI efficiency could be much lower than its potential when inadequately designed and improperly operated on a homogenous sandy soil profile [5]. Subsurface drip irrigation (SDI) is the latest advanced method of DI; it offers several advantages over alternative irrigation methods when adequately designed and installed and adopting best management practices [14]. Deficit or irrigation regime is well known as a water-saving irrigation method, but it is difficult to precisely quantify the optimum irrigation regime level in greenhouse tomato production [15].

The SDI has been appropriately used in arid land environments [16]. It applies irrigation water below the soil surface, within the root zone vicinity, by micro-irrigation emitters with discharge rates the same as the emitters of the DI on the soil surface [17]. Subsurface irrigation of automatic devices such as porous pipes, pots, and pitchers is a water-saving technology that minimizes evaporative losses and deep percolation [18].

Adoption of the SDI and implementation of a capillary barrier, a relatively fine-textured soil layer, effectively suppressed water by deep drainage and retained water in the shallow surface layer to more root water uptake by the strawberry [19]. The distribution pattern of water in layered soils was detected to be controlled by the layering sequence and position of the SDI drip line relative to the interface between soil layers [20]. The location of the SDI drip-line below the interface of coarse-over-fine layered soil resulted in more water, 89% distribution, in the fine sub-layer than 73% above the interface. Hence, selecting a drip-line depth when designing SDI for layered soils is essential to obtain an appropriate water and nutrient distribution that coincides with the expected adequate root depth. A wetted radius in layered-textured soils, sand-layer-over-clay-layer, was higher than in homogenous sand soils for particular emitter discharge [5].

Laboratory trials revealed that the wetting patterns and water distributions were significantly influenced by the sequence and thickness of soil layers and the application rate and volume [21]. An interface between layered soils was observed, whether a coarse-over-fine or fine-over-coarse, commonly performed by limiting downward water movement and increasing horizontal water movement [22]. Field experiments designated vertical and horizontal soil wetting from an SDI drip-line determined by the hydraulic properties (soil texture) and soil's initial soil moisture content [23]. It was shown that the low initial soil water content and the application rate increased the horizontal water distribution relative to the vertical from the drip line.

Horizontal water spreading from a drip line is essential in determining the required emitter spacing, the number of drip lines and emitters and the cost of the drip irrigation system. Dasberg [24] observed that the maximum water content zone occurred in the sub-layer immediately under the interface of the coarse-fine-layered soils. Thus, the radius on the soil surface and the wetted pattern depth are the essential factors of the wetted soil volume of an emitter [24]. Therefore, knowledge of the exact distribution of soil water around emitters is required to properly design and manage the SDI systems to provide the best water distribution in the root zone without excessive soil surface wetting and deep percolation [25]. High infiltration, high saturated hydraulic conductivity, and low water holding capacity of the coarse-textured sandy soils (41.7 to 50 mm/m) result in loss of nutrients and micronutrients by deep percolation drainage beyond the root system vicinity. The main part of the root system of vegetables, which uptakes water and nutrients, lies in the first foot (30.5 cm) under the soil surface. The study's objective was to impose a rich clay soil layer as a hydraulic barrier in a homogenous sandy soil profile of a low-tech greenhouse to evaluate and compare soil moisture distribution and water productivity of a grown tomato irrigated by conventional and modified surface drip irrigation.

2. Materials and Methods

The study experiment was conducted in a low-tech greenhouse at the research and training station of King Faisal University, Saudi Arabia (25°17.1347′ N and 49°29.1889′ E). The greenhouse housed a homogenous sandy soil profile with 90% sand, less than 10% clay and less than 1% organic matter. This profile extended uniformly to a depth of more than 100 cm. In the experiment, the following two factors were considered:

Two irrigation practices:
A: M-DI (Modified DI with hydraulic barrier);
B: DI (DI without hydraulic barrier).
Three irrigation regimes:
A: 100% of ETo (Full irrigation);
B: 75% of ETo (Deficit irrigation);
C: 50% of ETo (Deficit irrigation).

Initially, the greenhouse soil was sterilized with insecticidal and nematicidal (Furadan) products. Further, its ridges were enhanced with hydraulic barriers and rich clay soil layers inserted 15 cm from the soil surface. This thorough preparation of the soil ensures the integrity of our results. The physical, chemical and hydraulic properties of the amended soil profile of the ridges are shown in Table 1. Indoor climatic parameters (Temperature, relative humidity, wind speed, and radiation intensity) during the tomato's growth stages were measured using a multifunction meter data logger (model: DO 9847).

Table 1. Physical and chemical properties of the greenhouse soil and water.

Soil Profile	Depth (cm)	Sand%	Silt%	Clay%	Organic %	$CaCO_3$ %	EC (m/cm)	pH	K_s (cm/h)
Top homogenous sandy soil	1–15	90	4	6	0.9	4.1	1.33	7.9	26.2
Layered soil (sand-clay-sand)	15–30	50	20	30	4.8	17.4	0.71	7.8	-
Layered soil (sand-clay-sand)	30–50	48	20	32	4.7	15.2	1.27	7.7	-
Water Quality	EC (dS/m)		SAR		$CaCO_3$ (ppm)		NO_3 (ppm)		pH
Indicators	1.3		2.8		47		4.6		7.2

2.1. Experimental Design

Two-factorial experiment plots were set up as split-plot designs with three replications for each irrigation regime. The first factor consisted of two irrigation methods (DI and M-DI), while the second factor included three levels (100%, 75% and 50% of ETo) of irrigation regimes imposed by the two irrigation methods.

2.2. Amentment of Greenhouse's Ridges Homogenous Sandy Soil Profiles

The homogenous sandy soil profiles of the greenhouse ridges were amended by implementing rich clay soil layers. A groove of 22.5 cm deep and 30 cm wide was excavated along each ridge, as shown in Figure 1A. The rich clay soil was packed into the grooves at 7.5 cm thickness, as shown in Figure 1B. The upper 15 cm portion of the grooves was refilled with the sandy soil of the greenhouse to reset the ridges for the tomato plantation.

A ridge with a homogenous sandy soil profile (HSS) was left without a hydraulic barrier and used as the control.

Figure 1. Soil profile amendment for developing the M-DI. (**A**) Groove preparation; (**B**) grooves filled with clay soil.

2.3. Developing Subsurface Micro-Irrigation Method (M-DI)

A subsurface-micro-irrigation, M-DI, was developed as a water-saving technique by modifying the conventional surface drip irrigation method (DI). Polyvinyl chloride (PVC) pipes with plurality rectangular 45° slanted openings on two sides of the cylindrical walls were located under the drip-line emitters of the DI lateral. First plurality openings were made along the first portion of the cylindrical wall of a PVC pipe to the right side of a drip-line water flow direction, as shown in Figure 2. The second plurality of the slanted openings was created along a second opposing portion of the cylindrical wall.

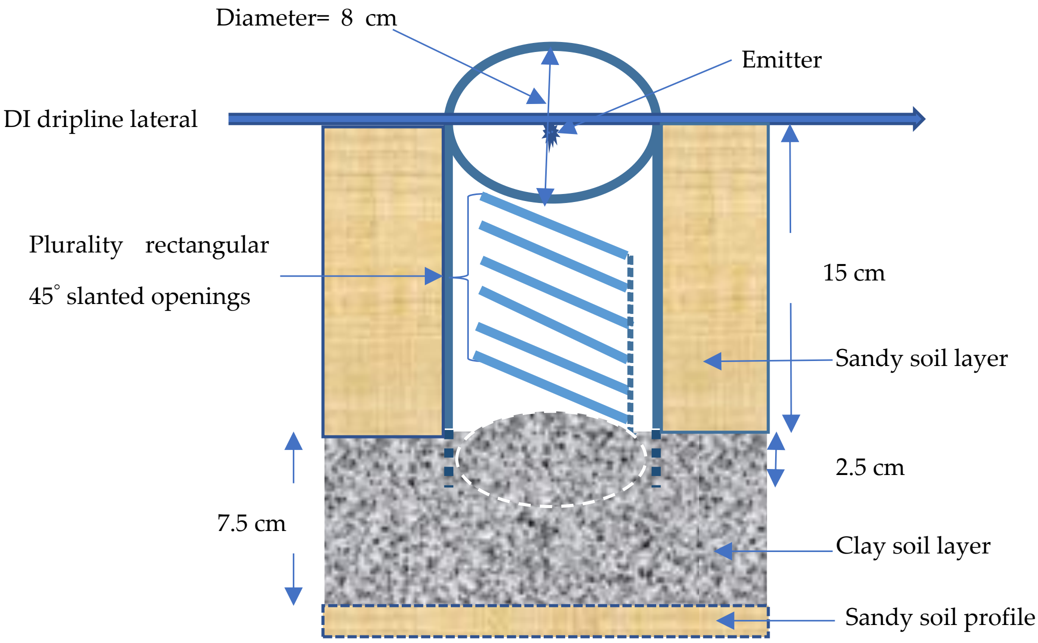

Figure 2. C.S. of M-DI-PVC pipe with 45° slanted openings.

The PVC pipes were wrapped with permeable textiles, as shown in Figure 3A, to prevent clogging of openings with soil particles. Then, the wrapped pipes were placed 2.5 cm into the rich clay soil layer with 40 cm spacing from each other along the middle of a ridge. The mixture of cattle manure and sandy soil of the greenhouse (3:1) was used to fill the PVC pipes up to 10 cm. Figure 3A,B of M-DI shows that each inline drip-line emitter coincided with a PVC pipe. The M-DI emitters' discharges were independent of soil type compared to the conventional SDI. This ensures that M-DI emitters are zero-clogging and can be maintained and replaced easily. When the mixture inside the PVC pipes becomes saturated with water, soil water is distributed horizontally through the slanted openings into the sandy layer above the clay layer. This movement is directed toward the roots of the plant lines on two sides of the drip-line, as illustrated in Figure 3C. The presence of a sandy layer under the rich clay soil layer, with its relatively higher saturated hydraulic Ks, plays a crucial role. It reduces the vertical movement of soil water, thereby increasing the horizontal movement into the clay layer. Therefore, the combined influence of the subsurface irrigation of the M-DI and the presence of a hydraulic barrier act as a water-saving practice. This combination effect controls the shape and position of the wetting zone, safeguarding water availability for the plant root uptake.

Figure 3. The process of setting the PVC pipes on the clay layer. (**A**) Wrapping of the PVC pipes; (**B**) fastening of drip-line emitters on the PVC pipes; (**C**) two plant lines irrigated by one drip-line.

2.4. Agronomic Practices and Yield

Seeds of the tomato (*Lycopersicon Esculentum* Mill., of cultivar Belqes F1) were treated with sodium hypochlorite solution (0.50%) for 10 min to surface-sterilize and rinsed with tap water. Afterward, the seeds were sown in a root cube growth medium. After 30 days, when the seedlings gained uniform size, they were transferred and transplanted into the greenhouse. Side shoots of the seedlings that appear in the junction between the stem and a branch of a tomato plant (tomato suckers) were removed, except those directly below the flower cluster. The growing point of the suckers pinched out, leaving only two leaflet branches. The fully ripened tomato fruits were picked six times during the growing season (March to May). Vegetative growth, fruit yield, and fruit yield components of the tomato were obtained.

2.5. Irrigation Measurements

A reservoir at an elevation of 214 m (a.s.l) was used to supply groundwater to the tomato crop with a salinity level of 1.3 dS m^{-1}. The reservoir has a pressure head of 60 m H_2O to the greenhouse irrigation system via a 63 mm polyethylene pipe, control valve and pressure regulator. As shown in Supplementary Materials (S1), two sets of smart timers were connected to solenoid valves and censored digital flow meters to manage the scheduling of irrigation water regimes. The maximum (100% of ETo) water requirement of a tomato plant per day was determined using a formula given by Hooshmanda et al. [26] as follows:

$$V = \frac{1}{1000} \times ET_o \times SA \quad (1)$$

where V is the volume of water irrigation (m^3), ETo is the potential evapotranspiration ratio (mm/d), and SA is the shadow area (m^2).

An average emitter discharge rate for the experimental subplots was determined by taking the mean discharges of all emitters in the subplots (lph). Then, the duration of irrigation was determined by using the following relation:

$$\text{Duration of irrigation} = \frac{\text{Volume of water to be applied (l)}}{\text{Average discharge of the emitters (lph)}} \tag{2}$$

2.6. Soil Moisture Measurement

The soil moisture of the sandy soil layer above the inserted clay layer was randomly measured with a hand-held soil moisture meter (HH2 of Delta-T Devices Ltd., London, UK) before irrigation was applied. This HH2 has a theta probe sensor (0–5 cm) that measures the volumetric soil moisture content in cubic water per cubic meter of soil meter (cm^3/cm^3). Measured soil moisture was obtained from the readout unit of the HH2 and manually documented. Furthermore, three soil moisture monitor tensiometers of different lengths (45 cm, 60 cm and 90 cm) were inserted for each irrigation regime treatment at the beginning of treatment to monitor the actual soil water tension in centibar [27]. Readings of the soil water tension of the sandy layer below the inserted clay soil layer for 30 cm, 50 cm and 70 cm from the soil surface for each regime treatment were taken during the tomato-growing season before irrigation time.

2.7. Water Productivity

Water productivity (WP) under the M-DI and the DI irrigation methods cultivations was determined by the ratio between the total economic yield of the greenhouse tomato (kg) and the amount of water applied (m^3) to a specific treatment during the growing season. It was computed using the following formula:

$$\text{WP} = \frac{\text{Economic yield}}{\text{Total applied irrigation water}} \tag{3}$$

2.8. Benefit/Cost Analysis

Benefit/cost analysis is an indicator employed to select the economically viable investment. It compares costs with benefits to determine the total benefit for the cost experienced [28,29]. The benefit/cost ratio matches investments for the selection of the project, with the highest benefit/cost ratio, defined by the following equation:

$$\frac{\text{Benefit}}{\text{cost}} = \frac{\text{BF}}{\text{C}} \tag{4}$$

where BF and C denote benefits and costs, respectively.

The benefits and costs of the two irrigation methods, conventional and modified surface drip irrigation, were compared for the greenhouse tomato fruit productivity and water use efficiency.

2.8.1. Break-even Levels of Production and Prices

To fix the number of units sold to cover the cost incurred in the production process, researchers use the break-even analysis, which defines the level of production at which an investment creates no profit but makes no losses [30]. The break-even point decides upon the number of units sold to attain the revenue essential to cover all the expenditures. The break-even point formula is obtained by the following:

$$\text{BEP} = \frac{\text{FC}}{\text{P} - \text{VC}} \tag{5}$$

where BEP, VC, FC and P represent the break-even level of production, variable cost, fixed cost and price per unit, respectively.

Production at the break-even level is a critical factor. It assures that the investment return shelters the cost of production (at the break-even point, the profit is zero; the return is equal to the cost). This understanding helps to identify when the investment is functioning at a loss or profit, depending on whether production is below or above break-even levels, respectively [31]. Break-even prices, which denote prices that cover costs at specific levels of sale, were estimated.

2.8.2. Revenues over Variable Cost and Revenues on Investment

The greenhouse production budget adopted by Ohio State University [32] was adjusted (using variable and fixed costs incurred by the two production systems) to estimate returns over variable costs and returns on investment.

The returns and costs were evaluated using existing prices in Saudi Riyals, providing a clear context for the financial analysis. The total cost, comprising variable and fixed costs, was calculated. Fixed cost, the cost of launching the investment, is incurred even if the production is zero. Variable cost, on the other hand, encompasses the cost of inputs used in production when the production process is in progress. Total and net returns were valued for each irrigation method by deducting total and variable costs from total returns, respectively.

For the approximation of fixed cost throughout the production, the authors employed a straight-line method [33] using the following formula:

$$\mathrm{fc} = \frac{\mathrm{pc} - \mathrm{rv}}{\mathrm{ul}} \tag{6}$$

where fc, pc, rv and ul signify fixed cost, primary cost, remaining value and the useful life of utilized fixed cost asset.

The substances of variables and fixed cost items for the two irrigation methods for low-tech greenhouse tomato production, namely conventional surface drip irrigation and modified surface drip irrigation, are presented in Supplementary Materials S2–S5. Implicit and Explicit costs were valued. Explicit costs characterize costs necessitating a direct outlay of money. In contrast, implicit costs represent costs that do not comprise a direct cash outlay but involve computing the opportunity cost of utilized resources.

3. Results

3.1. Actual Applied Irrigation Water

Smart timers based on the daily water requirement of a tomato plant set daily irrigation period times for the irrigation regimes. The daily average applied irrigation water per tomato plant growth cycle for the irrigation regimes (100%, 75% and 50% of ETo) using the M-DI and DI (100%ETo) was determined and shown in Figure 4. The results indicated that the total water requirement for tomatoes under the low-tech greenhouse using the M-DI irrigation regime levels at 100, 75 and 50 percent ETo were 51.19, 38.85 and 27.69 L/plant, respectively. Maximum daily-applied irrigation water of 1.4 and 1.1 L/plant received by the full irrigation regimes (100%ETo), respectively, by the M-DI and DI during the 12th week and the lowest by 50%ETo regime (0.14 L/plant) by the M-DI during the first week of the growing season.

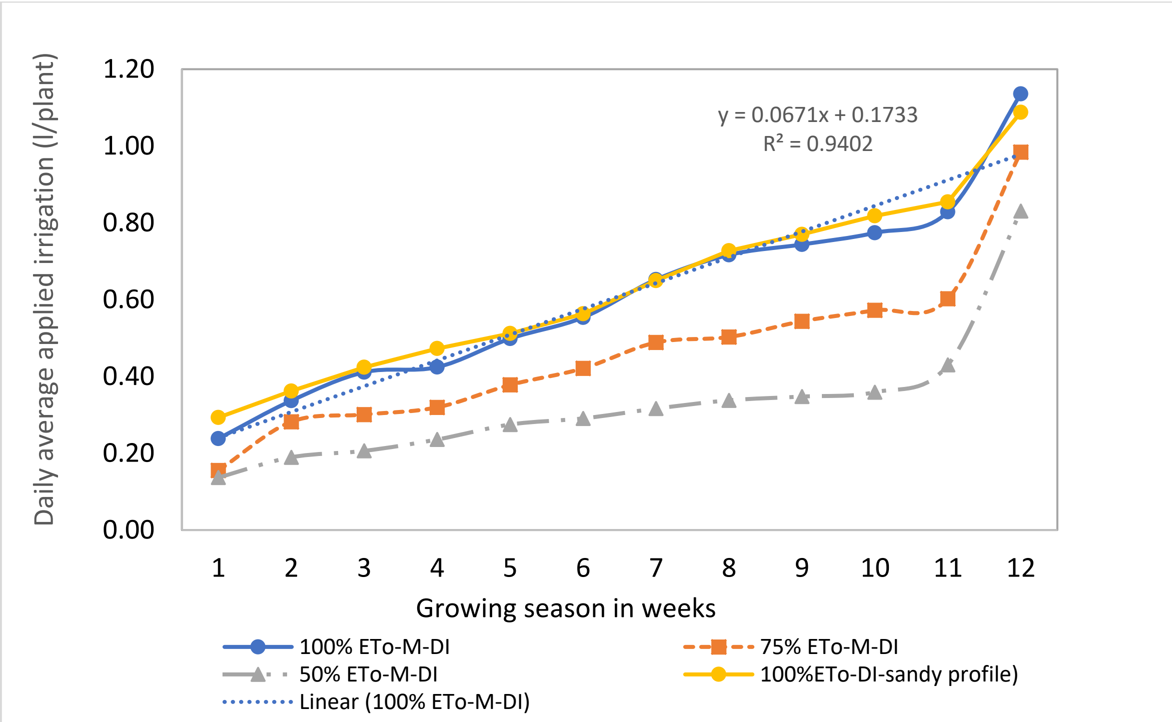

Figure 4. Actual irrigation regimes during the tomato-growing season.

3.2. Soil Moisture of the Sandy Soil Layer above the Clay Layer

The analysis of variance for soil moisture (0–5 cm) of sandy soil above the inserted clay layer as influenced by the type of irrigation method, irrigation regime, irrigation time and their interactions are revealed in Table 2. The M-DI and the DI irrigation methods significantly affected the surface soil moisture (0–5 cm) at an Alpha of 0.05. Similarly, the irrigation regimes (100%, 75% and 50% of ETo) and irrigation times (T) significantly impacted the surface soil moisture. Furthermore, all pair factor interactions were significantly different, except only the three-factor interactions were insignificantly different, as shown in Table 2.

Table 2. ANOVA of soil moisture for the irrigation methods, the regimes and the irrigation times.

Source	DF	SS	MS	F	P
Irrigation method (M-DI, DI)	1	0.170	0.170	57.78	0.0000
Irrigation regime (ETo)	2	0.060	0.030	10.14	0.0001
Irrigation time (T)	9	1.516	0.168	57.21	0.0000
M-DI,DI *ETo	2	0.034	0.017	5.69	0.0044
M-DI, DI *T	9	0.073	0.008	2.75	0.0059
ETo*T	18	0.462	0.026	8.72	0.0000
M-DI,DI *ETo*T	18	0.055	0.003	1.03	0.4307

Figure 2 reveals the least significant difference, pairwise compression, test of the soil moisture for the M-DI and DI irrigation methods with LSD of 0.0507. The highest significant difference in the soil moisture means occurred in the sixth week with a 100% increase, while the lowest occurred in the first week with a 13.3% increase due to the M-DI compared to the DI irrigation method, as shown in Figure 5.

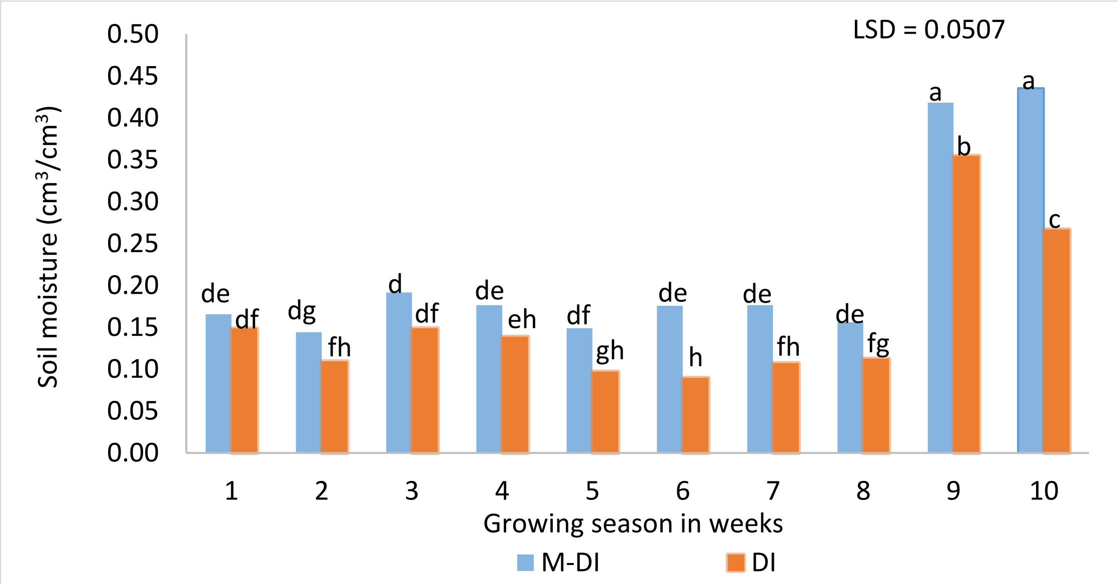

Figure 5. Soil moisture as influenced by irrigation methods. Different letters within the methods indicate a significant difference at $p < 0.05$.

Furthermore, Figure 6 revealed the interaction impacts of the irrigation methods and irrigation regimes on the soil moisture of sandy soil above the layer. The outcomes indicated for LSD of 0.0277, soil moisture means for interactions of the M-DI and DI with irrigation regimes of 100%ETo, 75%ETo, and 50%ETo were significantly different.

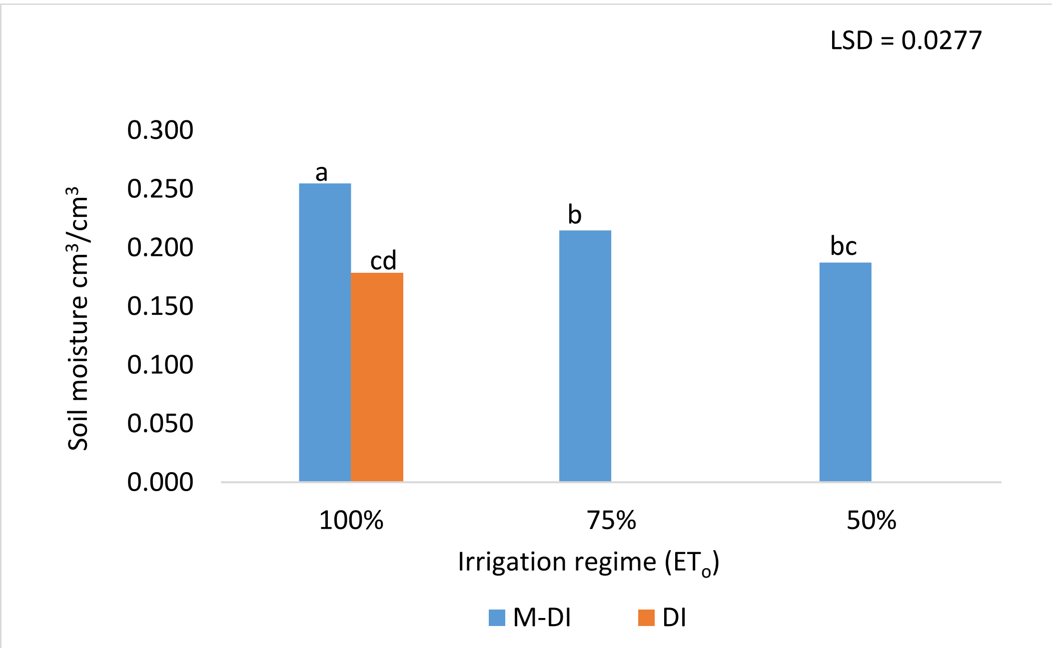

Figure 6. Soil moisture impacted by the methods and the regime interaction. Different letters within the irrigation methods indicate a significant difference at $p < 0.05$.

Moreover, under the M-DI method, the impacts of the interaction of the irrigation regimes and irrigation times for the soil moisture of the sandy soil above the clay barrier layer are shown in Table 3. The soil moisture levels were significantly different due to the interaction of the 100%, 75%, and 50% of ETo irrigation regimes and the irrigation times from 24 December until 11 February, at LSD of 0.062. However, the means of the soil moisture were insignificantly different due to the interaction of the irrigation regimes and the 25 February and 5 March irrigation times.

Table 3. Soil moisture (cm^3/cm^3) influenced by the interaction of irrigation regimes of M-DI and time of irrigation. Different letters within one row indicate a significant difference at $p < 0.05$.

Irrigation Time (T)	100%ETo	75%ETo	50%ETo
24-December	0.196IL	0.147HL	0.124FH
31-December	0.196L	0.097KL	0.087FH
7-January	0.218HL	0.149HL	0.144EG
14-January	0.228IL	0.120IL	0.125EF
21-January	0.151JL	0.110JL	0.108HK
28-January	0.160IL	0.117IL	0.122GJ
4-February	0.179HL	0.114JL	0.135FI
11-February	0.141HL	0.128IL	0.135HL
25-February	0.420A	0.317CD	0.261DE
5-March	0.401AB	0.331CD	0.322CD

3.3. Soil Matric Potential of the Sandy Soil Layer below the Clay Layer

The average soil matric potential (SMP) values of the ridges with hydraulic barriers obtained during the growth cycle of the tomato are shown in Figure 7. The higher the SMP of a Veda zone soil, the higher the effort of the root systems required to extract soil water. The means of the SMP at the 30 cm depth under the irrigation regimes of 50%, 75% and 100% of ETo were significantly lower than that at a depth of 50 cm and 70 cm. The SMP at the 30 cm depth was lower by 18.8% and 35.6%, respectively, compared to those at the 50 cm and the 70 cm depths. When considering the full irrigation (100%ETo) of M-DI, the SMP at the 30 cm depth was lower by 31.5% and 55.5%. However, for the full irrigation (100%ETo) of the DI, the SMP was equal at 30 cm and 50 cm depths and lower than that at a depth of 70 cm by 9.5%. These results were attributed to the clay soil barrier layer above the homogenous sandy soil layer. It effectively suppresses soil water movement by deep drainage and retaining it in shallow depth to increase root water uptake.

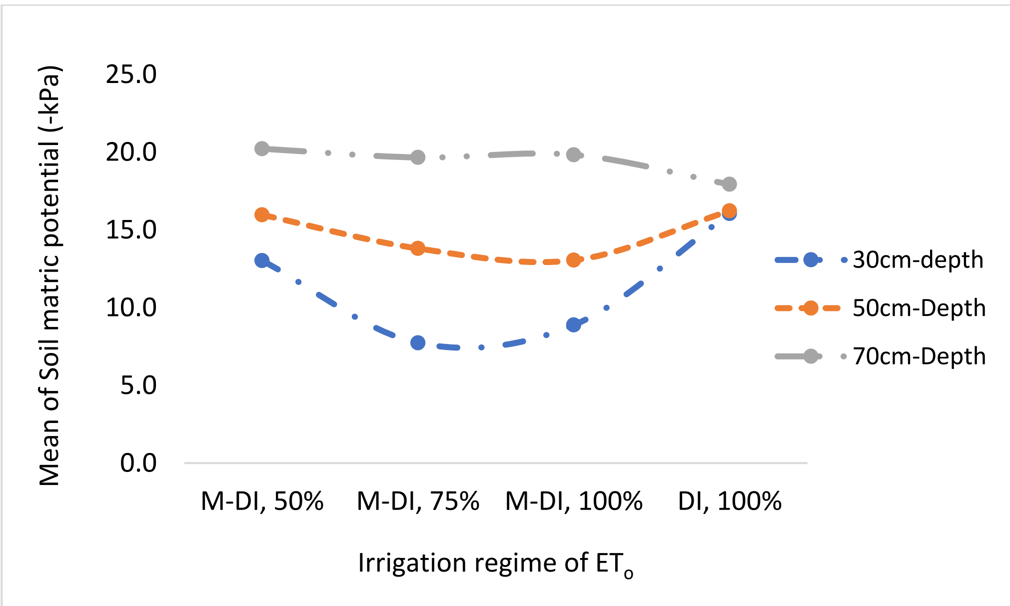

Figure 7. Soil matric potential of the sandy layer below the hydraulic barrier of clay soil.

3.4. Water Productivity

Fruit yield and water productivity of the low-tech greenhouse tomato improved with adopting the M-DI and amendment of homogeneous sandy soil profile ridges with barrier clay soil layers. As shown in Figure 8, under the clay layers-amended soil profile ridges and full irrigation (100%ETo) with the M-DI, the tomato fruit yield (TFY) increased by about 64.5% compared to the DI-applied irrigation to homogenous sandy soil profile ridges. Therefore, this increase in the TFY can be attributed to the availability of soil water and nutrients to root systems that are enhanced by the presence of the barrier layers and the adoption of the M-DI method. However, the TFY under the 50% and 75%ETo irrigation regimes of the M-DI, respectively, reduced by 3.9% and 7.8% compared to the full irrigation. The slight reductions in the TFY due to these irrigation regimes resulted in 50% and 25% savings in irrigation water. The average yield of tomato plants ranged from 3.1 kg/plant (control, homogenous soil profile) to 5.1 kg/plant (clay soil amended soil profile). The water productivity of the tomato for the full irrigation (100%ETo) of the M-DI with a hydraulic barrier was 54.7 kg/m^3, and for the DI without a hydraulic barrier was 32 kg/m^3.

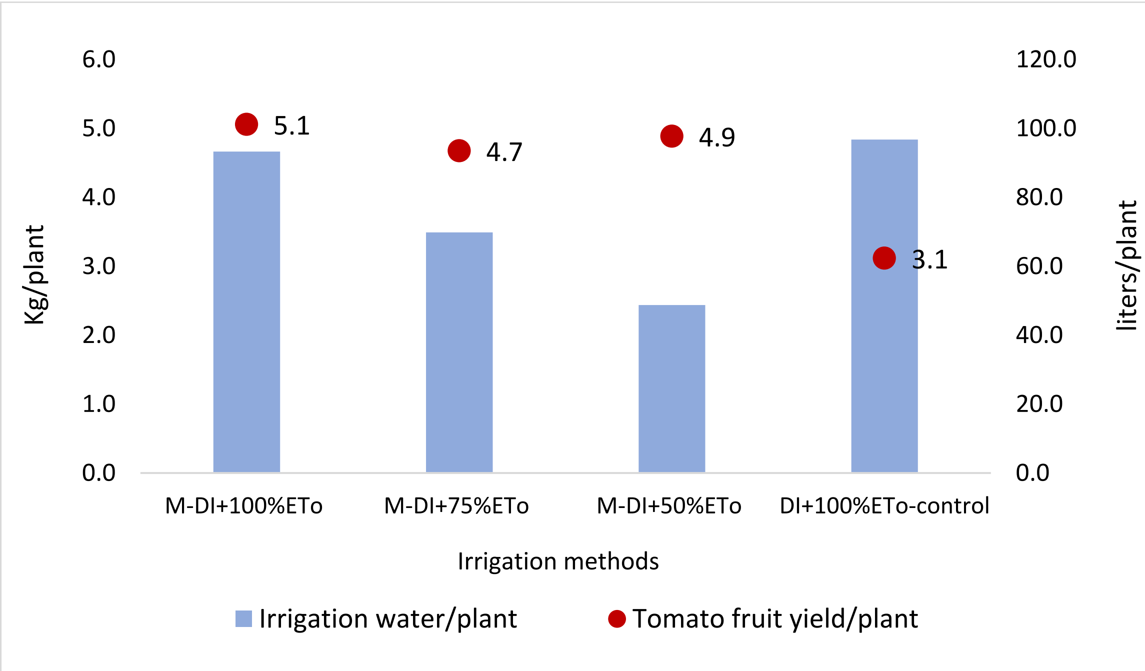

Figure 8. Tomato fruit yield and irrigation water applied by the M-DI and DI methods.

3.5. Economic of Tomato Fruit Production

According to Table 4, the fixed cost per square meter for modified surface drip irrigation (M-DI) under the three irrigation scenarios (M-DI,100%, M-DI, 75% and MDI, 50%) slightly exceeded that of conventional surface drip irrigation (DI) due to the materials added to modify the irrigation system. However, the exact value of variable cost for the two systems, estimated at 19.7 SR, is attributed to the similarity in variable cost items. The higher yield of tomatoes produced under the three irrigation scenarios of M-DI with clay soil layer barriers, compared to DI (control), resulted in higher returns and net returns, thus favoring the modified drip irrigation system. Variable cost exceeded fixed cost for both irrigation methods. This result could be designated to the extended useful life of fixed cost items, lowering depreciation values of fixed cost items. Table 5 demonstrates results related to the benefit/cost analysis for decisions related to the economic viability of the investment. Based on Table 5, the benefit/cost ratio favors the above results; the two irrigation methods are economically sustainable, where the benefit/cost ratio is equal to 3.6, 3.5, 3.4 and 2.3 for M-DI methods under irrigation regimes (100%, 75%, and 50%ETo) and the DI method, respectively. Hence, the M-DI for tomato cultivation verified domination over the DI method.

Table 4. Tomato fruit yield returns costs, revenues on investment and over variable cost for the M-DI methods under irrigation regimes (100%, 75%, and 50%ETo) and the DI method (control).

Method	DI (control)	M-DI, 50%	M-DI, 75%	M-DI, 100%
		Tomato fruit yield, returns and costs:		
Yield kg/m^2	8.32	13.2	12.7	13.6
Fixed cost/m^2	4.3	4.5	4.5	4.5
Variable cost/m^2	19.7	19.7	19.7	19.7
Price/kg	6.5	6.5	6.5	6.5
Return/m^2	54.08	85.8	82.6	88.4
VC + FC	24	24.2	24.2	24.2
net returns/m^2	30.08	61.6	58.4	64.2
Fixed cost/kg	0.52	0.34	0.35	0.33
Variable cost/kg	2.36	1.5	1.6	1.44
Total cost/kg	2.88	1.83	1.9	1.77
Profit/kg	3.62	4.6	4.5	4.73
Net Return on investment	1.25	2.5	2.4	2.6

Source: Author's computations based on Supplementary Tables S2–S6.

Table 5. Benefit/cost ratio for tomato production for the M-DI methods under irrigation regimes (100%, 75%, and 50%ETo) and the DI method (control).

Irrigation Method	Revenue per m^2 (SR)	(VC + FC)/m^2 (SR)	Benefit/Cost Ratio
Conventional surface drip irrigation (DI)	54.08	24	2.3
Modified surface drip irrigation (M-DI, 100%)	88.4	24.2	3.6
Modified surface drip irrigation (M-DI, 75%)	82.6	24.2	3.4
Modified surface drip irrigation (M-DI, 50%)	85.8	24.2	3.5

The break-even prices for tomato production under the two irrigation methods are shown in Supplementary Materials (S6) (net return at the break-even price equals zero). These findings are crucial for understanding the economic implications of different irrigation methods. The conventional surface drip irrigation method showed upper break-even prices for covering total and variable costs per kg, which could be attributed to higher variable and total cost per kg, together with inferior yield of tomatoes cultivated under the DI. Subtracting total cost per kg from market price and the net return per kg was equal to 3.62 and 4.73 for conventional and modified surface drip irrigation, respectively. The break-even yield for the conventional surface drip irrigation, estimated based on the break-even production level during the production period, was valued at around 1.05 kg/m^2, below the actual yield of 8.32 kg/m^2 by 7.27 kg/m^2. The break-even yield per square meter for the modified surface drip irrigation was valued at 0.9, which is below the actual yield of 13.6 kg/m^2 by around 12.7 kg/m^2 (Table 4 and Supplementary Materials "S2–S6"). The difference in break-even yield for the two irrigation methods originates from the gap in contribution margin, which is affected by variable cost per kg.

4. Discussion

The study recognizes the potential of saving irrigation water and increasing water productivity of greenhouse tomato crops by the adoption of modified surface drip irrigation and clay soil layer in ridges of homogenous sandy soil profile. Surface drip irrigation is commonly being adopted in most low-tech greenhouses of the eastern province of the KSA to conserve water while maintaining the economical production of vegetable crops. In the study region, Al-Ahsa, farmers were advised by the authority to accept surface drip irrigation as an efficient irrigation method in applying scarce water resources for vegetable crops compared to furrow irrigation in greenhouses [4,34]. The DI efficiency over furrow irrigation has been proven due to reduced labor costs and energy. In addition, it can improve crops' water use efficiency and reduce water losses caused by evaporation and deep percolation when designed and operated correctly [35]. However, there are some problems associated with drip irrigation (Surface and Subsurface) due to salt gathering and clogging emitters by small roots [34–36].

In this study, the modified surface drip irrigation combined with the insertion of a hydraulic barrier of the clay soil layer in ridges of the sandy soil profile enhanced horizontal soil moisture distribution within the root zones of tomato plants. The soil moisture levels under the M-DI method compared to the DI were more homogenous distributed during the first eight weeks of the tomato growing season. Moreover, moisture levels were significantly different during the last two weeks under the M-DI soil under the DI method. These outcomes were attributed to direct water application of the M-DI method via its PVC pipes and ponding of emitted water above the soil clay layer, which has low saturated hydraulic conductivity. Then, this ponding water resulted in a subsurface hydraulic gradient that horizontally delivered soil water via openings of two opposite sides of the PVC pipes towards the root zones of tomato plants [37]. These results agreed with Rodriguez-Sinobs et al. [38], who indicated that soil water content evolution behaves more homogenously under subsurface than under surface irrigation.

Soil moisture progression in the sandy layer below the clay soil layer, as related to measuring soil matric potential (SMP) at three depths (30 cm, 50 cm and 70 cm), was observed by tensiometers. The SMP values at a depth of 30 cm due to the M-DI's 75% and 100%ETo irrigation regimes indicated soil moisture levels were within the typical field capacity range of coarse-textured soils (<-10 kPa). On the other hand, at the depths of 50 cm and 70 cm, the suctions or the SMP values were greater than -10 kPa (Water Conservation Fact Sheet, BCMA, 2024). These aftereffects designated that the insertion of the barrier of the clay soil layer positively enhanced soil moisture availability at field capacity at the depth of 30 cm more than at the depths of 50 cm and 70 cm. Furthermore, the insertion of the barrier layer in the ridges of a homogenous sandy soil profile effectively suppressed soil water movement by deep drainage and retaining it in the shallow depth to more root zone water uptake. This conclusion agreed with the outcome of Noguchi et al. [19]. However, the SMP of the control at full irrigation (100%ETo) of the DI, at all depths in the homogenous sandy soil profile, were at suctions greater than the field capacity of the sandy soil. Therefore, soil water in homogenous sandy soil profile ridges moved down deeper by drainage and was not retained within the root zones of tomato plants.

Implementing the M-DI and the hydraulic barrier of clay soil in ridges of low-tech greenhouses that are dominated by homogenous sandy soil profiles resulted in increasing the TFY and water productivity. The study showed the water productivity improved by 70.9% due to full irrigation (100%ETo) of the M-DI and the barrier as compared to the control practice. The control practice was the combined effects of the DI and the homogenous sandy soil profile ridges. Furthermore, the irrigation regimes under the modified practice, i.e., using the M-DI and hydraulic barriers, significantly increased the water productivity by 70.2 kg/m^3 for the 75%ETo and 96.5 kg/m^3 for the 50%ETo. These outcomes agreed with the conclusions of Chand et al. [39], Singh et al. [40] and Shu et al. [41].

The benefit/cost analysis in this study showed that the modified practice (M-DI with barrier) was an economically more viable investment than the control practices (DI without barrier) in of low-tech greenhouse. Costs of the modified and the control practices were compared with benefits to decide the total benefit of the cost endured [27,28]. The higher TFY produced under the M-DI resulted in higher returns and net returns, thus favoring the M-DI method. It observed that the variable cost exceeded the fixed cost for both irrigation methods. This result could be attributed to the extended useful life of fixed cost items, lowering depreciation values of fixed cost items. Implementing the M-DI with a hydraulic barrier layer presented the upper break-even prices for covering total and variable costs per kg, which could be attributed to the higher variable and total cost per kg and the lower yield of tomatoes cultivated under the DI without a barrier layer.

5. Conclusions

Today, irrigation is the largest single consumer of fresh water. Competition for fresh water from other sectors would force irrigation to operate under water scarcity in the low-tech greenhouses of the KSA. The adoption of the modified drip surface irrigation method (M-DI) in a low-tech greenhouse with a homogenous sandy soil profile resulted in saving a significant amount of tomato irrigation compared to conventional surface drip irrigation (DI). Thus, the tomato fruit yield increased by 64.5% using the M-ID method with full irrigation (100%). Water productivity of the tomato under the full irrigation (100%ETo) of the M-DI with hydraulic barriers was enhanced by 71% as compared to the DI method without the hydraulic barriers. Economically, the M-DI demonstrated dominance over the DI regarding returns, yield, and profit; therefore, this outcome may boost farmers' incomes.

Implementing the M-DI in the low-tech greenhouse with a homogenous sandy soil profile and applying hydraulic barriers augmented the horizontal soil moisture distribution towards the root systems of tomato plants. Consequently, this optimized soil moisture distribution in the sandy layer above the barrier layer improved the fruit yield and water productivity of the tomato crop grown in a low-tech greenhouse. The study signified that the two irrigation methods are economically sustainable, with positive returns over total and variable costs. However, the modified surface drip irrigation method indicated superiority over conventional surface drip irrigation. Therefore, using M-DI with a hydraulic barrier layer of clay soil might improve soil moisture, water productivity, yield, and returns for crops in low-tech greenhouses under sandy soil conditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16202926/s1, Figure S1: Smart data loggers and router (left); Pressure regulator (right); Table S2: Total area cost of low-tech greenhouse (40 × 9 = 360 m^2) for DI title; Table S3: Total area cost of low-tech greenhouse (40 × 9 = 360 m^2) for M-DI; Table S4: Variable cost for DI in a low-tech greenhouse (40 × 9 = 360 m^2); Table S5: Variable cost for M-DI in a low-tech greenhouse (40 × 9 = 360 m^2); Table S6: Breakeven prices and levels of tomato production under the DI and M-DI methods under irrigation regime of 100%ETo.

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