sustainability

MDPI

Article

Integrated Agronomic, Hydraulic, and Economic Assessment of Subsurface Drip Irrigation Under Deficit Irrigation for Greenhouse Cucumber in Arid Saudi Arabia

Ahmed M. El-Feky *, Ahmed El-Shafei and Mohamed A. Mattar

Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, Riyadh 11451, Saudi Arabia; aelshafei1bn.c@ksu.edu.sa (A.E.-S.); mmattar@ksu.edu.sa (M.A.M.)
* Correspondence: aelfeky@ksu.edu.sa

Abstract

Improving irrigation efficiency is essential for sustaining greenhouse cucumber production in Saudi Arabia, where agriculture relies heavily on limited non-renewable groundwater resources. This study evaluated the combined effects of subsurface drip irrigation (SSDI) and regulated deficit irrigation on hydraulic performance, soil-water distribution, cucumber productivity, water-use efficiency, physiological response and economic return. A split-plot experiment with three replicates was conducted during a single growing season in greenhouses without supplemental lighting, using sandy soil containing 88.4–95.0% sand. Three irrigation levels (100%, 80%, and 60% of crop evapotranspiration, ETc) and three dripline types (XFD, UNIRAM, and REIN) were evaluated. Irrigation water had an ECw of 0.91 dS m^{-1} and a SAR of 4.5. Seasonal irrigation depths were 363, 294, and 226 mm, saving 18.8% and 37.7% water. Marketable yield declined from 99.5 t ha^{-1} at 100% ETc to 80.6 and 65.1 t ha^{-1} at 80% and 60% ETc, respectively, whereas irrigation water-use efficiency reached 72.0 kg m^{-3} at 60% ETc. XFD showed the highest hydraulic uniformity and generally maintained better crop performance. Leaf proline responses were dripline-dependent, with the highest concentration under XFD at 60% ETc. Under the experimental conditions, 80% ETc offered a practical compromise between yield maintenance and water saving. Under a fixed-water-budget scenario, reallocating water saved at 60% ETc increased the potential cultivated area and improved overall economic return, although this benefit was conditional on the availability of additional production capacity.

Keywords: *Cucumis sativus* L.; subsurface drip irrigation; deficit irrigation; emitter hydraulic performance; soil-water dynamics; irrigation water-use efficiency; fruit quality; leaf proline; economic assessment; arid agriculture; Saudi Vision 2030

Received: 5 July 2026
Revised: 18 September 2026
Accepted: 20 September 2026
Published: 3 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Water scarcity is not only a national concern but also a global challenge, with nearly 40% of the world's population experiencing serious water shortages [1]. In the Kingdom of Saudi Arabia (KSA), irrigation depends predominantly on non-renewable groundwater resources that have experienced severe depletion over recent decades [2]. With an average annual precipitation of only about 50 mm and agriculture accounting for more than 80% of national water withdrawals, pressure on groundwater resources continues to intensify [3]. Groundwater levels are projected to decline by approximately 0.181 m

annually through 2050, while rising temperatures, population growth, urban expansion, and increasing agricultural water demand are expected to further exacerbate pressure on the Kingdom's freshwater resources [4–6].

Climate change and the continued expansion of irrigated agriculture are expected to exacerbate water scarcity, particularly in arid and semi-arid regions. Although irrigation is essential for agricultural productivity and food security, intensive groundwater abstraction has raised serious concerns about the long-term sustainability of irrigated agriculture [7,8]. In Saudi Arabia, regional warming has occurred at nearly twice the global average, accompanied by a decline in annual precipitation of approximately 6.3 mm decade^{-1}, further increasing crop water requirements [9]. These challenges have prompted national initiatives, including Saudi Vision 2030 and the National Water Strategy 2030, to reduce dependence on non-renewable groundwater and improve agricultural water-use efficiency [10].

Greenhouse vegetable production represents an important component of Saudi agriculture, with cucumber (*Cucumis sativus* L.) ranking among the country's major protected crops. According to the General Authority for Statistics [11], Saudi Arabia operated more than 121,000 greenhouses in 2024, producing approximately 797,000 t of vegetables from 7800 ha, of which cucumber accounted for nearly 232,000 t. Because cucumber has a shallow root system, a high transpiration rate, and moderate sensitivity to water deficit, efficient irrigation management is therefore essential for maintaining yield, fruit quality, and water-use efficiency under protected cultivation.

Subsurface drip irrigation (SSDI) delivers water directly to the active root zone, thereby improving soil-moisture conditions, reducing crop water stress, enhancing nutrient delivery, and protecting driplines from surface damage [12,13]. Previous studies have shown that burying driplines can reduce evapotranspiration while improving crop growth compared with surface drip irrigation [14]. A recent meta-analysis of 145 studies reported that SSDI increased crop yield, water productivity, and irrigation water productivity by 12.3%, 15.3%, and 18.7%, respectively, compared with surface drip irrigation [15]. Soil-water distribution plays a key role in irrigation-system performance because it governs root-zone moisture availability and plant water uptake [16]. Wetting patterns are primarily influenced by soil hydraulic properties and irrigation application characteristics, including emitter discharge, spacing, and irrigation frequency [17–19].

Deficit irrigation (DI) is widely used to improve water-use efficiency (WUE) by reducing irrigation water during selected growth stages or throughout the growing season while minimizing yield losses [20]. Under greenhouse conditions, Ismail [21] reported that irrigation at 85% of field capacity saved 15% of irrigation water with a smaller yield penalty than irrigation at 70% of field capacity, which conserved more water but substantially reduced yield. Similarly, Rahil and Qanadillo [22] found that irrigation at 70% ETc improved cucumber growth, yield, and WUE while reducing seasonal irrigation water compared with conventional irrigation practices. Patanè et al. [23] reported that full irrigation maximized marketable tomato yield under semi-arid conditions, whereas deficit irrigation reduced yield less than proportionally to the applied water deficit and achieved irrigation-water savings of up to 48%. Regulated deficit irrigation deliberately applies less water than full ETc during drought-tolerant growth stages to improve water productivity while limiting yield losses [24,25]. Consistent with these findings, a meta-analysis of 185 vegetable studies reported an average yield reduction of only 6.9% when irrigation exceeded 80% of full ETc, with yield losses increasing markedly only below approximately 35% of full irrigation [26].

Beyond its effects on yield and water-use efficiency, deficit irrigation induces physiological and biochemical responses that reflect plant exposure to water stress. One such response is the accumulation of proline, an amino acid that functions as a compatible

osmolyte and contributes to osmotic adjustment, membrane stabilization, and protection against oxidative stress under water-limited conditions [27]. Leaf proline concentration is therefore widely used as a biochemical indicator of plant water-stress response. However, increased proline accumulation should be interpreted as evidence of exposure and physiological adjustment to water deficit rather than as direct evidence of improved drought tolerance or maintained crop productivity. In the present study, leaf proline was therefore measured alongside yield and water-use efficiency to provide a complementary physiological indication of cucumber response to the imposed irrigation deficits.

Despite previous research, important knowledge gaps remain regarding the combined application of subsurface drip irrigation (SSDI) and regulated deficit irrigation (RDI) for greenhouse cucumber production under arid conditions. First, the extent to which dripline hydraulic characteristics, including pressure compensation, manufacturing variation, and discharge stability, influence crop performance under deficit irrigation remains insufficiently understood, as most studies have evaluated emitter performance independently of crop response [28]. Second, the optimal balance between productivity, fruit quality, water-use efficiency, and economic return under different deficit irrigation levels has not been clearly established. Third, limited information is available on how irrigation water savings can be reallocated to increase cultivated area and farm profitability under a fixed water budget, consistent with the objectives of Saudi Vision 2030 [29].

To address these knowledge gaps, a split-plot experiment was conducted using three irrigation levels (100%, 80%, and 60% of crop evapotranspiration, ETc) and three subsurface driplines (XFD, UNIRAM, and REIN) installed at a depth of 15 cm in sandy soil under greenhouse conditions in central Saudi Arabia. The study integrated hydraulic performance, soil-water distribution, crop productivity, fruit quality, water-use efficiency, physiological response, and economic evaluation within a single experimental framework. In addition, it examined whether irrigation water saved through deficit irrigation could be reallocated to expand the cultivated area under a fixed water budget. Specifically, the objectives were to: (i) evaluate the hydraulic performance and soil-water dynamics of different driplines under deficit irrigation; (ii) quantify cucumber yield, fruit quality, and water-use efficiency; (iii) assess plant physiological response through leaf proline concentration; and (iv) determine the economic implications of alternative irrigation strategies under limited water availability.

2. Materials and Methods

2.1. Methodological Framework and Experimental Workflow

Figure 1 presents the integrated methodological framework and operational workflow used in this study. The framework links hydraulic, agronomic, and economic assessments within a single experimental and analytical sequence, allowing dripline performance, soil-water distribution, crop response, water-use efficiency, and economic outcomes to be evaluated collectively rather than as separate components. The overall procedure comprised nine operational steps, from characterization of the study site, soil, and irrigation water to hydraulic testing, field implementation, crop and soil-water monitoring, economic evaluation, and statistical analysis. The variables, equations, and performance indicators associated with these steps are summarized in Table 1.

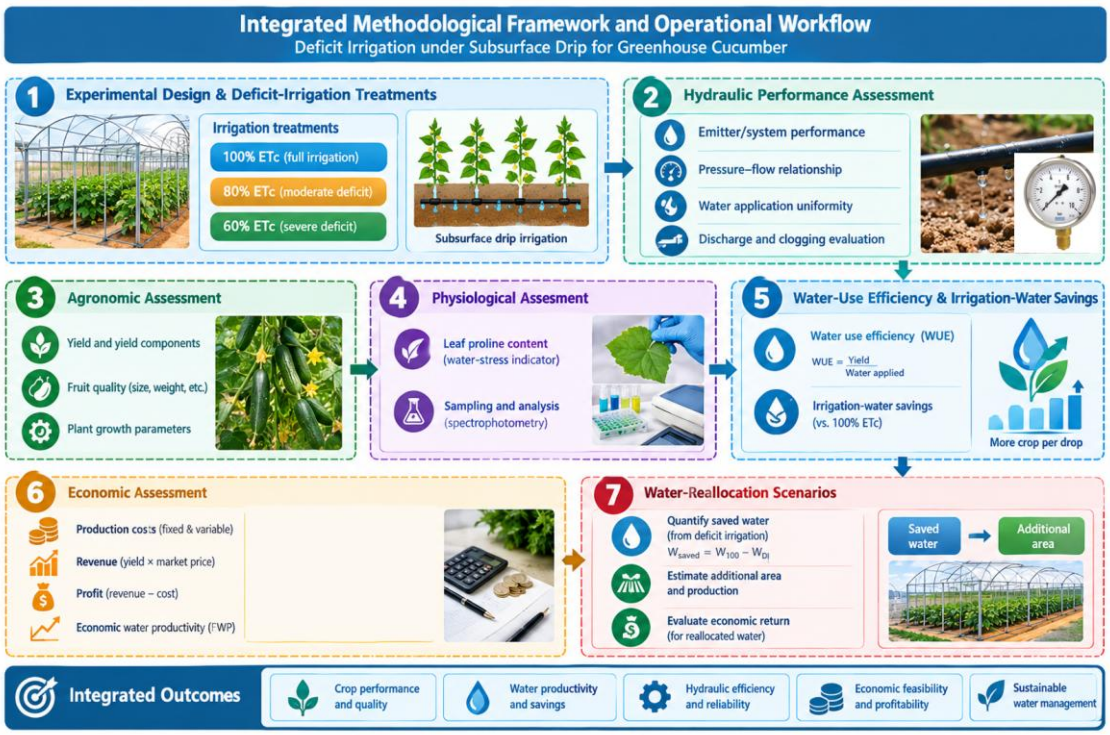


Figure 1. Integrated methodological framework and operational workflow linking the experimental design, hydraulic assessment, agronomic and physiological responses, water-use efficiency, economic evaluation, and water-reallocation analysis. Arrows indicate the flow of information among the principal components of the study, from irrigation-system evaluation and crop response to the integrated assessment of water productivity and economic performance. W100 is the full irrigation treatment and WDI is the dificit irrigation treatment.

Table 1. Methodological framework and nine-step operational workflow used in the integrated assessment.

Assessment Layer/Operational Step	Measurements and Analysis	Key Equations/Performance Indicators
Step 1. Characterization of the study site, soil profile, and irrigation water Quality (Section 2.1 and 2.2)	Study-site and greenhouse conditions; soil texture, field capacity, permanent wilting point, bulk density, pH, EC, and soluble ions; irrigation-water quality including ECw and SAR	Soil bulk density (Equation (1)); FAO irrigation-water quality criteria
Hydraulic layer	*Characterization of dripline hydraulic performance and water-application uniformity*	
Step 2. Laboratory evaluation of dripline hydraulic performance (Section 2.6)	XFD, UNIRAM, and REIN tested at 0.5, 1.0, 1.5, and 2.0 bar using 25 randomly selected emitters per dripline; discharge–pressure relationship determined as $q = kH^x$	Qvar, Cv, Ud, Eud, Euf, and UC (Equations (4)–(10))
Agronomic layer	*Evaluation of soil-water distribution and crop response under deficit irrigation*	
Step 3. Split-plot experimental design and SSDI installation (Section 2.3)	Three greenhouse blocks; irrigation levels of 100%, 80%, and 60% ETc as main plots; dripline types as subplots; laterals installed at 0.15 m depth, with emitters spaced 0.30 m apart and rows 0.80 m apart	Split-plot treatment structure
Step 4. Uniform crop management (Section 2.4)	Cucumber cv. Quantario RZ F1; identical transplanting, fertilization, pest management, and other cultural practices across treatments	Standardized crop-management conditions

Step 5. Crop water requirement and irrigation scheduling (Section 2.5)	ETo estimated from pan evaporation; ETc calculated using crop coefficients; daily irrigation applied at 100%, 80%, and 60% ETc	ETo = Kp × Epan; ETc = ETo × Kc (Equations (2) and (3))
Step 6. Greenhouse microclimate and soil-water monitoring (Sections 2.5 and 2.7)	Air temperature and relative humidity monitored; gravimetric soil-water content measured on a 4 × 4 grid around the emitter; spatial distribution mapped by ordinary kriging	Soil-water content and spatial wetting pattern
Step 7. Crop and physiological response assessment (Sections 2.8 and 2.9)	Marketable yield; fruit length, diameter, and weight; IWUE and WUE; leaf proline concentration as an indicator of plant response to water deficit	IWUE and WUE (Equations (11) and (12)); leaf proline concentration
Economic layer	*Assessment of costs, returns, sensitivity to selling price, and value of conserved irrigation water*	
Step 8. Economic, sensitivity, and water-reallocation analysis (Section 2.10)	Annualized fixed and variable costs; gross revenue; net profit; net profit-to-cost ratio; cucumber selling-price sensitivity at ±10%, ±20%, and ±30%; reallocation of saved water under a fixed total irrigation-water budget	CRF, TC, GR, NP, net profit-to-cost ratio, water saved, additional irrigable area, and total production
Statistical analysis	*Evaluation of irrigation, dripline, and interaction effects*	
Step 9. Statistical analysis (Section 2.11)	Split-plot ANOVA with greenhouse as block, irrigation level as main-plot factor, and dripline type as subplot factor; treatment means separated by LSD	Significance at $p \leq 0.05$

The hydraulic layer characterized the three subsurface driplines (XFD, UNIRAM, and REIN) under controlled laboratory conditions before field installation. The discharge–pressure relationship ($q = kH^x$) and six uniformity indices (Qvar, Cv, Ud, Eud, Euf, and UC) were determined at operating pressures of 0.5, 1.0, 1.5, and 2.0 bar using 25 randomly selected emitters per dripline (Section 2.5; Equations (4)–(10)). These measurements established the hydraulic performance of each dripline and provided the basis for interpreting subsequent differences in soil-water distribution.

The agronomic layer evaluated the characterized driplines in a split-plot greenhouse experiment, with irrigation level (100%, 80%, and 60% ETc) as the main-plot factor and dripline type as the subplot factor (Section 2.2). Irrigation requirements were determined from pan evaporation through ETo and ETc (Section 2.4; Equations (2) and (3)). Soil-water distribution around the emitters was quantified using gravimetric measurements on a 4 × 4 sampling grid and mapped by ordinary kriging (Section 2.6). Crop responses included marketable yield, irrigation water-use efficiency, water-use efficiency, physical fruit characteristics, and leaf proline concentration as an indicator of plant response to water deficit (Sections 2.7 and 2.8).

The economic layer used the measured irrigation and yield data to calculate annualized fixed and variable costs, gross revenue, net profit, and the net profit-to-cost ratio for each irrigation level × dripline combination (Section 2.9). It also included a selling-price sensitivity analysis and a water-reallocation scenario to examine the potential value of conserved irrigation water under a fixed total water budget. Statistical analysis constituted the final step of the workflow and was used to evaluate treatment effects within the split-plot design (Section 2.10).

The framework was structured to facilitate application beyond the specific driplines and irrigation levels evaluated here. Alternative dripline designs, deficit-irrigation levels, and local cost and price structures can be incorporated while retaining the same sequence of hydraulic characterization, agronomic assessment, and economic evaluation. This structure provides a reproducible basis for examining how irrigation-system performance and water-saving strategies translate into crop and economic outcomes under different production conditions.

2.2. Study Site and Soil Characterization

The experiment was conducted during the 2021–2022 growing season at the Educational Farm of King Saud University (24°43′ N, 46°37′ E; 612 m a.s.l.) in Riyadh, central Saudi Arabia. The region has a hyper-arid climate. Mean annual rainfall in the Riyadh region is approximately 90 mm, which is above the national average of about 50 mm reported for the Kingdom as a whole. Reference evapotranspiration is approximately 2300 mm yr^{-1} [30], and summer air temperatures frequently exceed 45 °C [30]. Regional warming has proceeded at nearly twice the global average, accompanied by a decline in annual precipitation of approximately 6.3 mm $decade^{-1}$ [9]. All treatments were carried out under identical greenhouse conditions to ensure uniform environmental exposure and minimize the influence of climatic variation on treatment responses.

Soil physical and chemical properties were determined following standard procedures [31]. Soil samples were collected to a depth of 45 cm to determine soil texture, field capacity (FC), permanent wilting point (PWP), bulk density, pH, electrical conductivity (EC), and the concentrations of major cations and anions. Soil texture was classified according to the USDA textural classification system. Field capacity (at 0.33 bar) and permanent wilting point (at 15 bar) were determined using a pressure membrane apparatus in the Soil Physics Laboratory, Department of Soil Science, King Saud University. Bulk density was determined from undisturbed soil cores (5.4 cm in diameter and 6.6 cm in height; volume = 151.1 cm^3) using Equation (1).

Bulk density was calculated as follows:

$$\rho_b = \frac{M}{V} \quad (1)$$

where ρ_b is the soil bulk density (g/cm^3), M is the oven-dry soil mass (g), and V is the volume of the soil core (cm^3). The measured physical and chemical properties of the experimental soil are presented in Table 1.

Irrigation Water Quality

Irrigation water was supplied from a single freshwater source at the Educational Farm of King Saud University and was distributed to all treatments through a common mainline. Water samples were collected during the growing season and analysed using standard laboratory procedures. Electrical conductivity (ECw) and pH were measured directly, while soluble cations and anions were determined according to standard methods [32] and APHA [31]. The measured chemical characteristics of the irrigation water are presented in Table 2.

Table 2. Physical and chemical parameters of the soil.

Parameters	0–15 cm	15–30 cm	30–45 cm
	Particle size (%)		
Sand	88.4	93	95
Silt	3.0	2.0	3.0
Clay	8.1	5.0	2.0
Textural class	Loamy sand	Sandy	Sandy
FC (%)	24.6	25.8	22.6
PWP (%)	13.5	13.6	11.9
ρ_b (g cm^{-3})	1.6	1.6	1.6
pH	8.0	8.0	8.1
EC (dS m^{-1})	0.4	0.6	1.3
	Cations, meq/L		
Ca^{2+}	2.0	2.0	2.0

Mg^{2+}	4.0	4.7	4.0
Na^{+}	1.1	0.4	0.9
K^{+}	0.6	0.4	0.5
	Anions, meq/L		
CO_3^{2-}	6.7	6.2	5.8
HCO_3^{-}	Tr.	Tr.	Tr.
SO_4^{2-}	0.7	0.8	1.0
Cl^{-}	0.5	0.4	0.6

Tr. = trace; FC, field capacity; PWP, permanent wilting point; ρ_b, bulk density; EC, electrical conductivity. Cations and anions were determined in the soil saturated-paste extract. Irrigation-water composition is presented separately in Table 2.

The suitability of the water for irrigation was assessed according to the guidelines of Ayers and Westcot [32]. The irrigation water had an ECw of 0.91 dS m^{-1}, a pH of 8.0, and an SAR of 4.5. Sodium and chloride concentrations were 118 and 115 mg L^{-1}, respectively. Based on the applicable FAO criteria, the water presented a slight-to-moderate restriction on use, primarily associated with salinity and the combined effect of ECw and SAR on soil-water infiltration. Because water was applied through subsurface drip irrigation, criteria related specifically to foliar injury from sprinkler or overhead application were not directly applicable.

The same water source was used for all irrigation levels and dripline treatments throughout the experiment. Consequently, irrigation-water quality remained consistent among treatments and was not a source of treatment-to-treatment variation.

2.3. Experimental Design

A split-plot experimental design with three greenhouse blocks was used. Each of the three identical fibreglass-covered greenhouses (36 m^2 each) contained all three irrigation levels: I100 (100% ETc), I80 (80% ETc), and I60 (60% ETc). Within each greenhouse, the irrigation levels were randomly assigned to the main plots. Each main plot was subsequently divided into subplots to which the three dripline types (XFD, UNIRAM, and REIN) were randomly assigned. Thus, greenhouse represented the blocking and replication factor, irrigation level was the main-plot factor, and dripline type was the subplot factor. Randomization of both irrigation levels and dripline treatments was conducted independently within each greenhouse. The experimental layout, including the main-plot and subplot structure and replication within each greenhouse, is illustrated in Figure 2.

The three driplines were selected to represent contrasting hydraulic behaviors among commercially available subsurface drip irrigation systems rather than to compare specific brands. They differed in pressure-compensating behaviour, sensitivity of emitter discharge to operating pressure, manufacturing variation, and discharge uniformity. These contrasts provided an experimental basis for examining whether differences in emitter hydraulic performance were reflected in soil-water distribution and crop response under regulated deficit irrigation. Accordingly, XFD, UNIRAM, and REIN are used throughout the manuscript as experimental identifiers, while the broader interpretation focuses on their hydraulic characteristics rather than their commercial identity.

All driplines were installed at a depth of 0.15 m, with emitters spaced 0.30 m apart and rows spaced 0.80 m apart. The nominal emitter discharge was 3.5 L h^{-1} at an operating pressure of 100 kPa, following the experimental configuration described by Abedin [33]. Each irrigation mainline was controlled by an independent valve, and irrigation scheduling and water application were managed automatically using a Hunter ACC controller. Irrigation was applied daily from 21 days after planting until harvest according to the irrigation duration and schedule prescribed for each treatment.

2.4. Plant Material and Crop Management

Cucumber (*Cucumis sativus* L.) cv. Quantario RZ F1 (Rijk Zwaan, The Netherlands) was used in the experiment. Seedlings were raised in nursery trays and transplanted 20 days after sowing at the three-true-leaf stage. Plants were spaced 0.30 m within rows and 0.8 m between rows. Standard greenhouse cucumber management practices used at the KSU Educational Farm, including plant training, fertigation, and pest and disease management, were applied uniformly to all treatments following recommended crop-management practices [34]. All crop-management practices other than the experimental irrigation treatments were kept consistent across treatments throughout the growing season.

2.5. Crop Water Requirements and Irrigation Scheduling

Reference evapotranspiration (ETo) was estimated from evaporation measured using a Colorado sunken pan installed inside the greenhouse. A pan coefficient (Kp) of 1.10 was used to convert measured pan evaporation (Epan) to ETo. This value is within the range reported by FAO for Colorado sunken pans, for which Kp varies according to pan surroundings, wind conditions, relative humidity, and fetch [35]. Crop coefficient (Kc) values corresponding to the cucumber growth stages were 0.50 during the initial stage, increasing to 1.15 during the mid-season stage [35]. The mid-season value exceeds the FAO-56 tabulated value for cucumber (1.00) and was adopted to account for the vertically trained canopy and the enclosed greenhouse environment. Because fruits were harvested continuously until the end of the experiment, the late-season reduction in Kc was not applied [35,36]. Reference evapotranspiration and crop evapotranspiration were calculated as follows:

$$ET_o = ET_p \times K_p \quad (2)$$

$$ET_c = ET_o \times K_c \quad (3)$$

where ET_o is the reference evapotranspiration (mm), K_p is the pan coefficient, E_{pan} is the measured pan evaporation (mm), ET_c is the crop evapotranspiration (mm), and K_c is the crop coefficient. The irrigation depth applied to each treatment was determined from the calculated ET_c for each growth stage at 100%, 80%, or 60% ET_c, and the corresponding irrigation volume was calculated on an area basis.

Because the laterals were installed below the soil surface, irrigation was delivered only to the wetted soil strip formed around each lateral rather than to the entire soil surface. Accordingly, the seasonal irrigation depths refer to the wetted strip, and the corresponding irrigation volumes per unit land area were obtained by multiplying the applied depth by the wetted-area fraction. With a lateral spacing of 0.80 m and a mean wetted strip width of 1 m, the wetted-area fraction was 0.40. The seasonal depths of 362.76, 294.17, and 225.94 mm under 100%, 80%, and 60% ETc therefore corresponded to 1451.1, 1177.9, and 904.7 m^3 ha^{-1} of land area, respectively, and these volumes were used in the calculation of irrigation water-use efficiency and in the economic analysis.

Throughout the experimental period, air temperature and relative humidity inside the greenhouses were continuously recorded at canopy level using digital sensors. Air temperature ranged from 12.7 to 35.0 °C, while relative humidity varied from 26 to 80%. Solar radiation and vapor pressure deficit were not directly measured inside the greenhouses. The three greenhouses were maintained under comparable environmental and management conditions to minimize differences in microclimate among experimental blocks.

2.6. Laboratory Evaluation of Dripline Hydraulic Performance

The hydraulic performance of the three driplines was evaluated at the Department of Agricultural Engineering, King Saud University. Each dripline was tested at operating pressures of 0.5, 1.0, 1.5, and 2.0 bar. The physical and hydraulic characteristics of the tested driplines are presented in Table 3. The discharge–pressure relationship was described by $q = kH^x$ and fitted using least-squares regression, where q is the emitter discharge, H is the operating pressure head, k is the emitter coefficient, and x is the discharge exponent. For each dripline, 25 emitters were randomly selected, and emitter discharge was measured volumetrically over a 1-min collection period. Emitter discharge was not re-measured in situ after installation in the greenhouses. Accordingly, the hydraulic indices reported in Table 4 represent laboratory-based characterization of the manufacturing and pressure-response properties of the evaluated driplines rather than direct measurements of their realized discharge under greenhouse field conditions.

Table 3. Chemical characteristics and FAO-based interpretation of the irrigation water used in the experiment.

Parameter	Unit	Measured Value	FAO Interpretation for Irrigation Use
pH	—	8.0	Within the normal range (6.5–8.4)
Electrical conductivity (ECw)	dS m^{-1}	0.91	Slight–moderate restriction
Calcium (Ca^{2+})	mg L^{-1}	13	—
Magnesium (Mg^{2+})	mg L^{-1}	23.5	—
Sodium (Na^{+})	mg L^{-1}	118	See note [1]
Potassium (K^{+})	mg L^{-1}	5.7	—
Carbonate (CO_3^{2-})	mg L^{-1}	0	—
Bicarbonate (HCO_3^{-})	mg L^{-1}	178	See note [2]
Chloride (Cl^{-})	mg L^{-1}	115	No restriction for root uptake
Sulphate (SO_4^{2-})	mg L^{-1}	138	—
SAR	(—)	4.5	Slight–moderate infiltration restriction [3]

Notes: [1] Sodium-related infiltration effects were evaluated using SAR in combination with ECw rather than Na^{+} concentration alone. [2] The FAO bicarbonate criterion considered here relates primarily to foliar effects under sprinkler irrigation and is therefore not directly applicable to the present SSDI system. [3] Infiltration restriction was interpreted from the combined ECw–SAR relationship according to Ayers and Westcot [32]. A dash (—) indicates that no specific FAO degree-of-restriction classification was assigned to the individual parameter.

Hydraulic performance was assessed using emitter discharge variation (Q_{var}) [36], the manufacturer's coefficient of variation (C_V) [37], statistical uniformity (U_d), design emission uniformity (E_{ud}), field emission uniformity (E_{uf}), and Christiansen's uniformity coefficient (UC). These indices were calculated using Equations (4)–(10).

$$Q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \times 100, \quad (4)$$

where q_{max} and q_{min} are the maximum and minimum emitter flow (m^3/s) along the line, respectively.

$$C_v = \frac{S_d}{\bar{q}} \times 100, \quad (5)$$

$$S_d = \sqrt{\frac{\sum_{i=1}^{n}(q_i - \bar{q})^2}{n-1}}, \quad (6)$$

where S_d is the standard deviation of the emitter discharge rate, $\bar{q}$ is the average value of the emitter discharge rate, n is the total number of emitters along the lateral line, and q_i is the discharge rate of the emitter. In Equations (7) and (8), Cv is expressed as a fraction rather than as a percentage.

$$U_d = (1 - C_v) \times 100, \quad (7)$$

$$E_{ud} = \left(1 - \frac{1.27C_v}{\sqrt{N_p}}\right) \times \frac{q_{min}}{\bar{q}} \times 100, \quad (8)$$

where q_{min} is the minimum emitter discharge rate and N_p is the number of emitters per plant. In Equation (10), qi is the discharge of the i-th emitter and qa is the mean emitter discharge, equivalent to the average discharge rate defined above.

Eu_f describes how uniformly the overall system can distribute water from each emitter [38] and could be estimated from:

$$E_{uf} = \frac{q_{min}}{\bar{q}} \times 100, \quad (9)$$

$$Uc = 100\left[1 - \frac{1}{n\bar{q}} \sum_{i=1}^{n} |qi - qa|\right] \quad (10)$$

Table 4. Physical and hydraulic characteristics of the tested driplines.

Dripper Lines	Nominal Diameter (mm)	Discharge (L/h)	Wall Thickness (mm)	x: Emitter Exponent	Pressure Range (bar)	Pressure Compensating	Emitter Spacing (cm)	A Picture for Emitters
XFD	16.6	3.5	1.2	0.034	0.5–4.0	Yes	30	
UNI-RAM	17	3.5	1.2	0.047	0.58–4.14	Yes	30	
REIN	16	3.5	1	0.27	0.5–3.5	No	30	

2.7. Soil Water Content and Spatial Distribution

Soil-water distribution was assessed for each irrigation × dripline treatment combination using three replicate experimental units. In each replicate, soil samples were collected on a 4 × 4 spatial grid comprising 16 sampling points positioned consistently relative to the nearest emitter (Figure 3). Samples were collected at four lateral distances from the emitter (0, 15, 30, and 45 cm) and four soil depths (5, 20, 35, and 50 cm), and the same sampling coordinates were used for all treatments. Measurements were conducted on a single occasion during the late growth stage, 24 h after irrigation and immediately before the subsequent daily irrigation event. Soil water content (SWC) was determined gravimetrically, and the resulting measurements were used to characterize the spatial distribution of water within the soil profile. Two-dimensional soil-water distribution maps were generated by ordinary kriging using Surfer v.15 (Golden Software) with a spherical

variogram model. Horizontal distance from the emitter and soil depth were used as the spatial coordinates, while measured SWC was used as the interpolation variable [39].

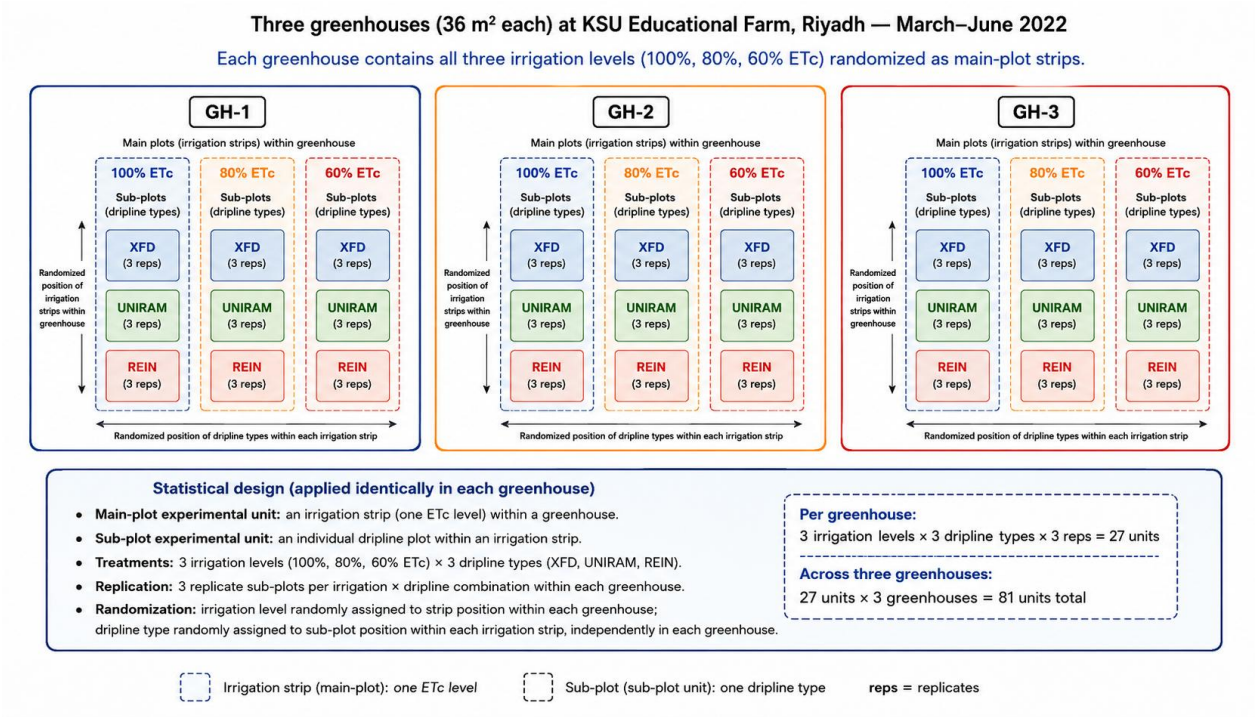


Figure 2. Experimental layout of the split-plot design showing the three irrigation levels (100%, 80%, and 60% ETc) as main plots and the three subsurface dripline types (XFD, UNIRAM, and REIN) as subplots within each of the three greenhouse blocks. Each irrigation × dripline combination included three replicate subplots within each greenhouse.

2.8. Yield, Water-Use Efficiency, and Physical Fruit Quality

Irrigation water-use efficiency (IWUE) was defined as the marketable yield produced per unit of irrigation water applied, whereas crop water-use efficiency (WUE) was defined as the marketable yield produced per unit of crop evapotranspiration (ETc). These indices were used to evaluate crop productivity relative to irrigation supply and crop water use, respectively. IWUE and WUE were calculated according to Howell [40] using Equations (11) and (12), respectively:

$$\text{IWUE (kg m}^{-3}) = \frac{Y}{IWA}, \quad (11)$$

$$\text{WUE (kg m}^{-3}) = \frac{Y}{ETc} \quad (12)$$

where Y is the total marketable yield (kg ha^{-1}), IWA is the irrigation water applied per unit cropped area (m^3 ha^{-1}), and ETc is crop evapotranspiration expressed as the equivalent water volume per hectare (m^3 ha^{-1}). Physical fruit quality was evaluated using a representative subsample of 30 fruits from each subplot, pooled across three harvests. Fruits were randomly selected from the harvested lot at a uniform marketable maturity stage to minimize variation associated with developmental stage and harvest timing. Fruit length (L), fruit diameter (D), and individual fruit weight (W) were measured for each sampled fruit. The resulting values are presented as treatment means with standard deviations.

2.9. Leaf Proline Analysis

Proline is an amino acid that commonly accumulates in plant tissues in response to water deficit and is widely used as a biochemical indicator of plant water-stress response.

In the present study, free proline content was measured in fully expanded leaves as an indicator of the physiological response to the imposed irrigation treatments, rather than as a quality attribute of the harvested fruit. Free proline was determined using the acid-ninhydrin method described by Bates et al. [41]. Fresh leaf tissue (0.5 g) was homogenized in 5 mL of 3% sulfosalicylic acid and centrifuged at 12,000× *g* for 10 min. One millilitre of the supernatant was mixed with 1 mL of acid-ninhydrin reagent (1.25 g ninhydrin dissolved in 30 mL glacial acetic acid and 20 mL of 6 M H_3PO_4) and 1 mL of glacial acetic acid. The reaction mixture was heated at 100 °C for 1 h and then cooled in an ice bath. Proline was extracted with 4 mL of toluene, and absorbance was measured at 520 nm against a toluene blank. Proline concentration was determined from an L-proline standard curve and expressed as μmol g^{-1} fresh weight (FW).

2.10. Economic Analysis

An economic analysis was conducted following the approaches described by Amosson et al. [41] and Lamm and Trooien [42]. The analysis was structured to compare the economic performance of the irrigation level × dripline combinations and to assess the potential economic value of irrigation water conserved through deficit irrigation.

2.10.1. Economic Indicators and Cost Boundary

The economic assessment was conducted as a partial-budget analysis restricted to costs that differed among the irrigation level × dripline combinations and to seasonal production costs directly attributable to crop production. Costs common to all treatments and invariant among them, including the greenhouse structure and land, were excluded from the cost boundary because they did not affect the relative comparison among treatments. The economic indicators considered were annualized fixed cost, seasonal variable cost, total production cost, gross revenue, net profit, net profit-to-cost ratio, and irrigation water required per unit of production.

2.10.2. Data Sources and Parameter Selection

The purchase costs of the XFD, UNIRAM, and REIN driplines were 0.23, 0.22, and 0.15 USD m^{-1}, respectively, and the manifold cost was 0.34 USD m^{-1}; these values were obtained from the respective suppliers. Fittings and other installation expenses were estimated at 30% of the total pipeline cost, while trenching and lateral installation costs were approximately 0.23 USD m^{-1}, following Amosson et al. [41] and Lamm and Trooien [42]. An economic life of eight years and an annual interest rate of 4% were assumed for the irrigation system.

Fixed costs included the annualized irrigation-system investment, whereas variable costs included irrigation water, energy at 0.07 USD kWh^{-1}, labor, fertilizers, pesticides, and other directly attributable seasonal production costs. Costs originally expressed in US dollars were converted to Saudi riyals (SAR) at an exchange rate of 3.75 SAR USD^{-1}. A baseline cucumber selling price of 3.5 SAR kg^{-1} (approximately 0.93 USD kg^{-1}) was used for the revenue calculations. This value was treated as an analytical baseline rather than as a fixed or nationally representative market price because cucumber prices may vary with season, market supply, and marketing channel. Its influence on the economic results was therefore examined separately through sensitivity analysis.

For the economic calculations, postharvest and transport losses were assumed to account for 10% of total production. Of the production remaining after these losses, 70% was assumed to meet marketable grade and was valued at the baseline cucumber selling price, while the remaining 30% was classified as non-graded production and was not included in gross revenue. These assumptions were applied consistently across all irrigation level × dripline combinations.

2.10.3. Calculation Procedure

For each irrigation level × dripline combination, annualized fixed cost was calculated from the initial irrigation-system investment using the assumed economic life and annual interest rate. Seasonal variable cost was obtained by summing the directly attributable costs of irrigation water, energy, labor, fertilizers, pesticides, and other seasonal production inputs. Total production cost was calculated as the sum of annualized fixed and seasonal variable costs.

For the production-side calculations, the 10% allowance for postharvest and transport losses was first deducted from total production. Of the remaining production, 70% was classified as graded marketable production and used to calculate gross revenue at the baseline cucumber selling price of 3.5 SAR kg^{-1}. Net profit was calculated as gross revenue minus total production cost, and the net profit-to-cost ratio was calculated as net profit divided by total production cost. Irrigation water required per unit of production was calculated by dividing the seasonal irrigation volume by the corresponding total production. All calculations were performed separately for each irrigation level × dripline combination.

2.10.4. Water-Reallocation Scenario

A hypothetical water-reallocation scenario was developed to assess the potential use of irrigation water conserved through deficit irrigation to expand the cultivated area while maintaining the same total irrigation-water budget. The analysis assumed that: (i) the water saved per unit area was fully available for irrigation elsewhere; (ii) suitable additional land was available for expansion; (iii) sufficient capital was available for additional greenhouse structures, irrigation infrastructure, and land preparation; (iv) labor, energy, and other production inputs could be scaled in proportion to the expanded area; (v) the additional production could be absorbed by the market at the assumed selling price; and (vi) yield per unit area on the additional land was equivalent to that measured experimentally under the corresponding irrigation treatment.

The additional irrigable area, expressed as a fraction of the originally irrigated area, was calculated as

$$f = \frac{V_{100} - V_d}{V_d} \quad (13)$$

where V_{100} and V_d are the seasonal irrigation volumes under full and deficit irrigation ($m^3\ ha^{-1}$), respectively. Total production obtainable under the fixed water budget was then calculated as

$$P_t = Y_d(1 + f) \quad (14)$$

where P_t is the total production (t) and Y_d is the yield obtained under the deficit treatment ($t\ ha^{-1}$).

The operational feasibility of this scenario depends on the availability of suitable additional land, sufficient capital for greenhouse and irrigation infrastructure, the ability to scale labor and other production inputs, and market capacity to absorb the additional production. The reported costs correspond to the originally equipped area and do not include the incremental capital and operating expenditures required to bring the additional area into production. Consequently, the net profit and net profit-to-cost ratio derived from the reallocation scenario represent upper-bound estimates of the potential economic value of conserved irrigation water, rather than realized whole-farm returns. The scenario should therefore be interpreted as a resource-allocation exercise rather than as a prediction of commercial farm profitability.

2.10.5. Sensitivity Analysis

The sensitivity of the economic results to cucumber selling price was evaluated using a one-way sensitivity analysis. The baseline selling price of 3.5 SAR kg^{-1} was varied by ±10%, ±20%, and ±30%, while treatment yields and production costs were held constant. Gross revenue and net profit were recalculated for each irrigation level × dripline combination at each price level. The analysis was used to determine the extent to which variation in cucumber selling price affected absolute profitability and whether it altered the relative economic ranking of the treatment combinations.

2.11. Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) according to the split-plot experimental design. Greenhouse was treated as the blocking and replication factor, irrigation level (100%, 80%, and 60% ETc) as the main-plot factor, and dripline type (XFD, UNIRAM, and REIN) as the subplot factor. The irrigation level × dripline interaction was also included in the analysis. The effect of irrigation level was tested against the greenhouse × irrigation level interaction as the main-plot error term, whereas the effects of dripline type and the irrigation level × dripline interaction were tested against the subplot error. When significant differences were detected, treatment means were separated using the least significant difference (LSD) test at $p \leq 0.05$. Statistical analyses were performed using CoStat software, version 6.303 (CoHort Software, Monterey, CA, USA).

3. Results

3.1. Hydraulic Performance of the Three Driplines

Table 5 summarizes the hydraulic performance indices of the three driplines at an operating pressure of 100 kPa. XFD showed the lowest manufacturer's coefficient of variation (C_v = 0.021) and discharge variation (Q_{var} = 5.54%), together with the highest Christiansen's uniformity coefficient (UC = 98.25%). UNIRAM showed comparable hydraulic performance, with a C_v of 0.026, Q_{var} of 7.08%, and U_C of 97.83%. In contrast, REIN had the highest C_v (0.077) and Q_{var} (14.70%) and the lowest statistical uniformity (U_d = 92.38%) among the tested driplines. Overall, XFD and UNIRAM exhibited more uniform emitter discharge than REIN.

Table 5. Hydraulic performance indices of the tested driplines at an operating pressure of 100 kPa (mean of 25 emitters per dripline).

Performance Parameter	Symbol	XFD	UNIRAM	REIN	ASABE [37] Class
Variance of discharge	Q_{var} (%)	5.5	7.1	14.7	Qvar < 10 = desirable
Manufacturer's coefficient of variation	C_v	0.021	0.026	0.077	Cv < 0.05 = excellent
The statistical uniformity coefficient	U_d (%)	97.9	97.4	92.4	Ud ≥ 90 = excellent
Design emission uniformity	E_{ud} (%)	96.7	96.2	90.3	Eud ≥ 90 = excellent
Field emission uniformity	E_{uf} (%)	97.4	97	92.4	Euf ≥ 87 = good
The water application uniformity Christiansen's	UC (%)	98.2	97.8	94.7	UC ≥ 90 = excellent
Discharge exponent	x	0.034	0.047	0.27	x ≈ 0 = full PC

3.2. Irrigation Water Applied and Water Savings

The establishment period was excluded from deficit irrigation. All treatments received the same irrigation for the first three weeks after transplanting, with deficit treatments imposed from Week 4 until harvest. Thus, I100, I80, and I60 represent 100%, 80%,

and 60% of ETc applied from Week 4 onward. Consequently, seasonal irrigation reductions were 18.8% and 37.7%, rather than 20% and 40%.

As shown in Table 6, all treatments received the same irrigation depth during the first three weeks after transplanting, and the deficit-irrigation treatments were imposed from Week 4 onward. Seasonal irrigation depth was 362.76 mm under 100% ETc and decreased to 294.17 and 225.94 mm under 80% and 60% ETc, respectively. These reductions corresponded to irrigation-water savings of 18.8% and 37.7% relative to full irrigation. Weekly irrigation requirements generally increased with crop development and reached a maximum of 48.32 mm at Week 12 under the 100% ETc treatment.

Table 6. Weekly crop evapotranspiration and irrigation water applied during the cucumber growing season.

Growth Stage		E_{pan} (mm)	K_c	K_p	ET_o (mm)	ET_C (mm)	IWA (mm)	100% (mm)	80% (mm)	60% (mm)
Initial	Week 1	12.2	0.5	1.10	13.42	6.71	7.77	7.77	7.77	7.77
	Week 2	9.2	0.5	1.1	10.12	5.06	5.86	5.86	5.86	5.86
	Week 3	11.9	0.5	1.1	13.09	6.6	7.64	7.64	7.64	7.64
Development	Week 4	21.90	0.61	1.1	24.09	14.79	17.11	17.11	13.69	10.27
	Week 5	16.50	0.76	1.1	18.15	13.8	15.97	15.97	12.77	9.58
	Week 6	27.2	0.89	1.1	29.92	26.7	30.91	30.9	24.72	18.54
	Week 7	26.0	1.04	1.1	28.6	29.84	34.54	34.54	27.63	20.72
Mid-Season and Late	Week 8	23.0	1.15	1.1	25.3	29.04	33.61	33.61	26.89	20.16
	Week 9	26.5	1.15	1.1	29.15	33.5	38.8	38.8	30.75	23.06
	Week 10	27.50	1.15	1.1	30.25	34.79	40.26	40.26	32.2	24.16
	Week 11	27.80	1.15	1.1	30.58	35.17	40.7	40.70	32.56	24.42
	Week 12	33.00	1.15	1.1	36.30	41.75	48.32	48.32	38.65	28.99
	Week 13	28.20	1.15	1.1	31.02	35.67	41.29	41.29	33.03	24.77
	Total	290.9			319.99	313.43	362.76	362.76	294.17	225.94

E_{pan} is evaporation from the pan, K_c is a crop coefficient, K_p is a pan coefficient, ET_o is the reference evapotranspiration, ETc is crop evapotranspiration, and IWA is the irrigation water applied.

3.3. Soil Water Distribution

The kriged soil-water distribution maps showed clear differences in soil water content (SWC) with irrigation level, soil depth, and dripline type (Figures 4–6). Under 100% ETc, the wetting pattern extended farther both laterally and vertically than under the deficit-irrigation treatments. SWC was generally lower in the upper 0–15 cm soil layer and increased at greater depths, particularly below 30 cm. XFD and UNIRAM produced more uniform soil-water distribution patterns, whereas REIN showed greater spatial variation and locally higher SWC values (Figure 4). For reference, the measured field capacity and permanent wilting point of the experimental soil were 24.6–25.8% and 11.9–13.6%, respectively (Table 1).

At 80% ETc, the wetted zone became smaller than under full irrigation (Figure 5). For XFD, SWC near the emitter reached approximately 14% and gradually decreased with increasing distance and depth. UNIRAM showed a similar range of SWC, whereas REIN produced a wider range of approximately 8–18% within the upper 30 cm of the soil profile. Across the three driplines, soil moisture was highest near the emitter and generally decreased with increasing horizontal distance.

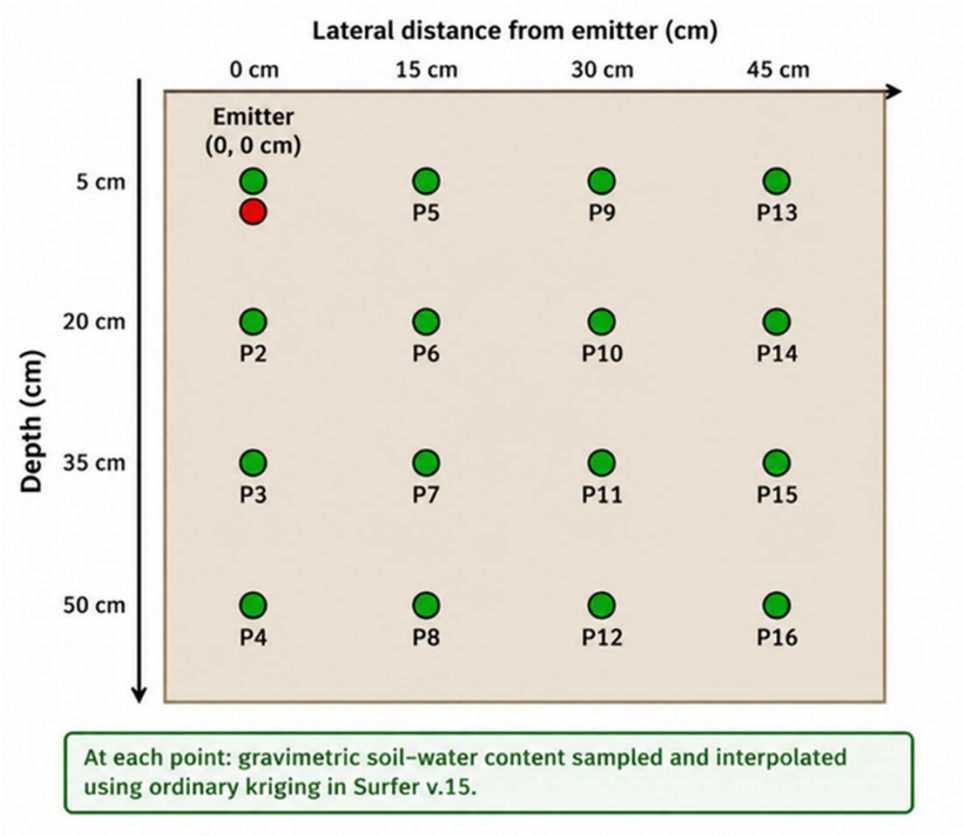


Figure 3. Spatial arrangement of the 4 × 4 soil-sampling grid used to determine gravimetric soil-water content (SWC), showing the 16 sampling points at four lateral distances from the emitter (0, 15, 30, and 45 cm) and four soil depths (5, 20, 35, and 50 cm). The red point is the emitter.

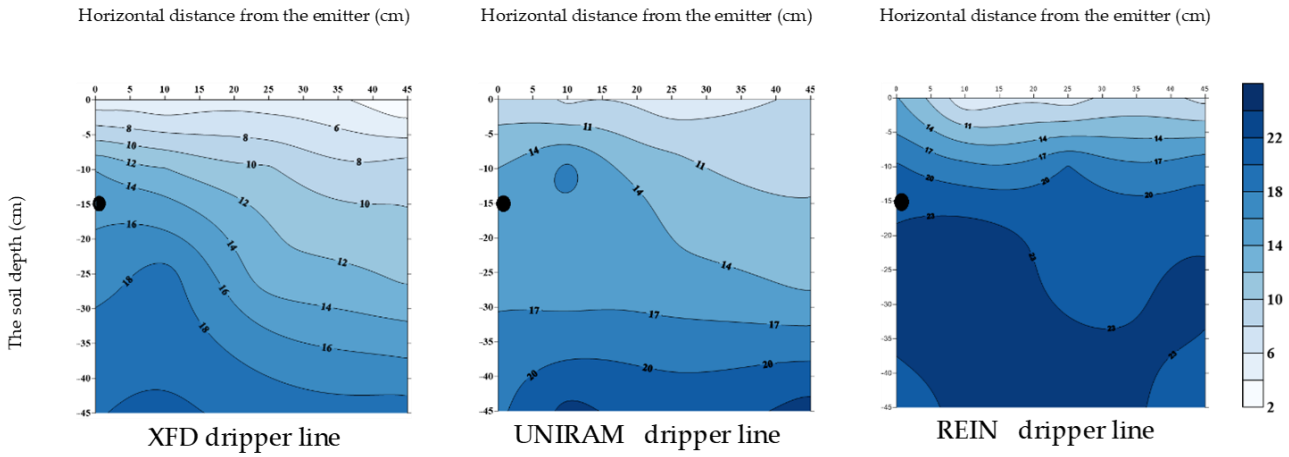


Figure 4. Kriged soil-water distribution maps under SSDI at 100% ETc. The emitter is located at 15 cm.

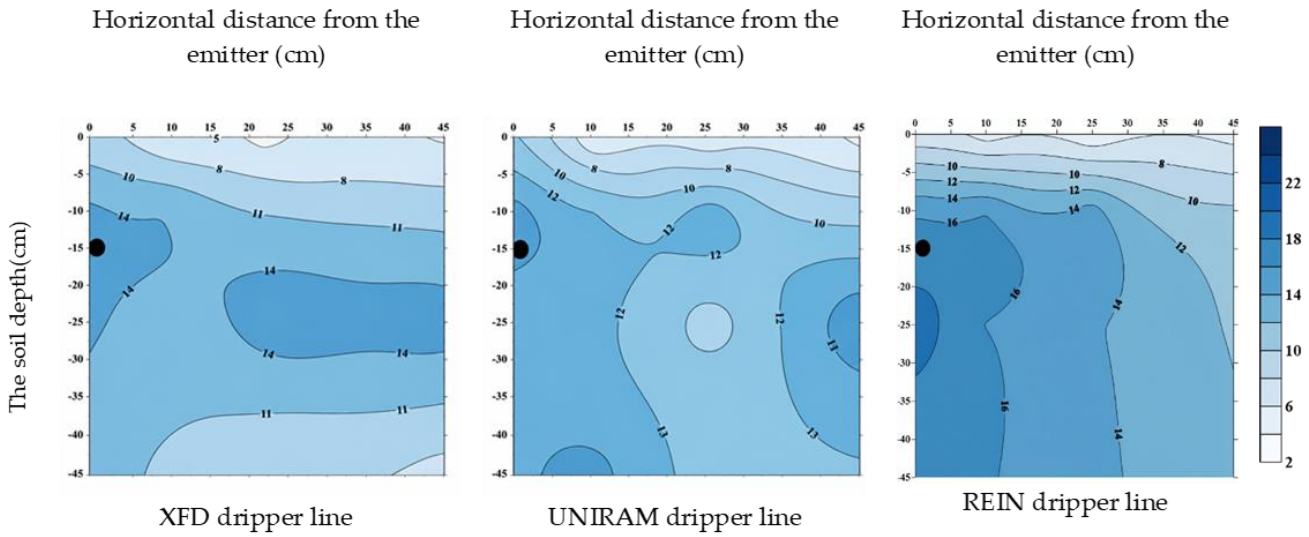


Figure 5. Kriged soil-water distribution maps under SSDI at 80% ETc. The emitter is located at 15 cm.

Under 60% ETc, the wetting pattern contracted further and water remained concentrated around the emitter (Figure 6). The XFD dripline produced a relatively uniform moisture pattern within the 0–30 cm soil layer, whereas greater spatial variation was observed with REIN. Overall, the kriged maps showed that the size and intensity of the wetted zone decreased with irrigation level. The approximate dimensions of the wetted zone were 35 × 35 cm under 100% ETc, 28 × 30 cm under 80% ETc, and 22 × 25 cm under 60% ETc. No surface ponding was observed during the experiment.

3.4. Crop Yield

The effects of irrigation level and dripline type on total yield, early yield, and fruit number per plant are presented in Table 6. Irrigation level significantly affected all yield components ($p < 0.001$). Total yield decreased from 99.5 t ha^{-1} under 100% ETc to 80.6 and 65.1 t ha^{-1} under 80% and 60% ETc, respectively, corresponding to reductions of 19.0% and 34.6%. Early yield showed a similar response, declining by 18.9% and 34.3% under 80% and 60% ETc, respectively. Fruit number per plant also decreased from 23.2 under full irrigation to 20.0 and 17.1 under 80% and 60% ETc, representing reductions of 13.8% and 26.3%, respectively.

Dripline type also significantly affected cucumber yield. XFD produced the highest mean total yield (92.4 t ha^{-1}), followed by UNIRAM (85.6 t ha^{-1}) and REIN (67.1 t ha^{-1}). Compared with XFD, total yield was 7.4% lower with UNIRAM and 27.4% lower with REIN. A similar pattern was observed for early yield. Fruit number per plant did not differ between XFD and UNIRAM (20.5 fruits plant^{-1}) but was significantly lower with REIN (19.3 fruits plant^{-1}).

The irrigation level × dripline interaction was not significant for total yield, early yield, or fruit number per plant ($p > 0.05$). Nevertheless, the highest total yield was recorded for XFD under 100% ETc (110.9 t ha^{-1}), whereas the lowest was obtained for REIN under 60% ETc (53.6 t ha^{-1}).

3.5. Irrigation Water-Use Efficiency (IWUE) and Water-Use Efficiency (WUE)

Irrigation level significantly affected both IWUE and WUE (Table 7). The highest IWUE was recorded under 60% ETc (72.02 kg m^{-3}), which was approximately 5% higher

than the values obtained under 100% and 80% ETc (68.5 and 68.4 kg m^{-3}, respectively). Similarly, WUE increased to 83.4 kg m^{-3} under 60% ETc, compared with 79.3 and 79.2 kg m^{-3} under 100% and 80% ETc, respectively. No significant difference in either efficiency index was observed between the 100% and 80% ETc treatments.

Table 7. Effects of irrigation level, dripline type, and their interaction on cucumber yield components.

		Water Applied (m^3 ha^{-1})	Total Marketable Yield (t ha^{-1})	Early Marketable Yield (t ha^{-1})	No. Fruit per Plant
Irrigation levels					
100%		1451.1	99.5 a	17.5 a	23.2 a
80%		1177.9	80.6 b	14.2 b	20.0 b
60%		904.7	65.1 c	11.5 c	17.1 c
LSD 0.05			3.1	0.6	1.62
p value			0.0000 ***	0.0000 ***	0.001 **
Dripper lines					
XFD			92.4 a	16.1 a	20.5 a
UNIRAM			85.6 b	15.1 b	20.5 a
REIN			67.1 c	11.8 c	19.3 b
LSD 0.05			4.7	0.8	0.6
p value			0.0000 ***	0.0000 ***	0.001 **
Irrigation levels × Dripper lines					
100%	XFD		110.9 a ± 5.9	19.5 a ± 1.1	24 a ± 2
	UNIRAM		104.1 ab ± 2.83	18.3 ab ± 0.5	24 a ± 2
	REIN		83.5 cd ± 10.5	14.7 cd ± 0.2	21.7 b ± 1.7
80%	XFD		93.7 bc ± 5.2	16.5 bc ± 0.9	20.3 b ± 3.1
	UNIRAM		83.6 cd ± 0.8	14.7 cd ± 1.8	20 b ± 2
	REIN		64.4 ef ± 7.2	12.7 de ± 1.3	19.6 bc ± 1.2
60%	XFD		72.5de ± 7.5	12.2 e ± 2.8	17.5 cd ± 1
	UNIRAM		69.4 e ± 16.3	11.3 ef ± 1.2	17.2 d ± 1.8
	REIN		53.6 f ± 1.9	9.4 f ± 0.3	16.6 d ± 1.5
LSD 0.05			–	–	–
p value			0.4 ns	0.2 ns	0.1 ns

The mean values in each column followed by different letters are significantly different at $p \leq 0.05$. The mean values followed by the same letters within each factor are not significantly different. LSD: least significant difference. *p* value: the probability value. ns: non-significant. ** mean $p < 0.01$; *** mean $p < 0.001$.

Dripline type significantly affected both IWUE and WUE ($p < 0.001$). XFD produced the highest mean IWUE and WUE values of 78.7 and 91.1 kg m^{-3}, respectively, followed by UNIRAM with 73.1 and 84.7 kg m^{-3}. REIN recorded the lowest values, with an IWUE of 57.2 kg m^{-3} and a WUE of 66.1 kg m^{-3}. Compared with XFD, IWUE was approximately 7.1% lower with UNIRAM and 27.3% lower with REIN.

Although water-use efficiency increased as irrigation was reduced, this increase should not be interpreted independently as an improvement in overall agricultural performance. IWUE represents yield per unit of irrigation water applied, and in the present study the highest value coincided with the lowest absolute marketable yield. Reducing irrigation from 100% to 60% ETc increased IWUE from 68.5 to 72.0 kg m^{-3}, an increase of approximately 5%, while marketable yield decreased from 99.5 to 65.1 t ha^{-1}, representing a reduction of 34.6% as shown in Table 8. Thus, the gain in water productivity was relatively modest compared with the associated yield penalty. Physical fruit attributes

showed a similar response: under XFD, mean individual fruit weight decreased from 201.3 g at 100% ETc to 156.1 g at 60% ETc, accompanied by reductions in fruit length and diameter. These changes may have commercial implications because cucumber marketability is influenced by fruit size and appearance. Accordingly, water-use efficiency should be evaluated together with absolute yield, physical fruit attributes, and economic return rather than used as an independent criterion for selecting an irrigation strategy.

Table 8. Effects of irrigation level, dripline type, and their interaction on IWUE and WUE.

		IWUE (kg/m³)	WUE (kg/m³)
Irrigation levels			
100%		68.5 b	79.3 b
80%		68.4 b	79.2 b
60%		72.0 a	83.4 a
LSD 0.05		2.8	3.26
p value		0.04 *	0.04 *
Dripper lines			
XFD		78.7 a	91.1 a
UNIRAM		73.1 b	84.7 b
REIN		57.2 c	66.1 c
LSD 0.05		4.6	5.4
p value		0.0000 ***	0.0000 ***
Irrigation levels × Dripper lines			
100%	XFD	76.4 ab ± 4.1	88.5 ab ± 4.8
	UNIRAM	71.7 b ± 2	82.9 b ± 2.2
	REIN	57.5 c ± 7.3	66.6 c ± 8.5
80%	XFD	79.5 a ± 4.5	92.1 a ± 5.2
	UNIRAM	71.1 b ± 0.7	82.2 b ± 0.8
	REIN	54.6 c ± 6.1	63.2 c ± 7.08
60%	XFD	80.1 a ± 8.3	92.8 a ± 9.6
	UNIRAM	76.7 ab ± 18	88.7 ab ± 20.8
	REIN	59.2 c ± 2.1	68.6 c ± 2.4
LSD 0.05		–	–
p value		0.76 ns	0.76 ns

The mean values in each column followed by different letters are significantly different at $p \leq 0.05$ (least significant difference). The mean values followed by the same letters within each factor are not significantly different. LSD: least significant difference. *p* value: the probability value. ns: non-significant. * mean $p < 0.05$; *** mean $p < 0.001$.

3.6. Leaf Proline Response to Deficit Irrigation

Leaf proline content varied with irrigation level and dripline type (Figure 7). Mean proline concentrations across driplines increased from 12.3 μmol g^{-1} FW under 100% ETc to 14.0 and 14.7 μmol g^{-1} FW under 80% and 60% ETc, respectively. Under XFD, leaf proline increased progressively as irrigation decreased, from 12.07 to 16.87 to 18.55 μmol g^{-1} FW at 100%, 80%, and 60% ETc respectively. However, proline did not increase with deficit under UNIRAM. Values were 14.20, 14.05, and 13.15 μmol g^{-1} FW, which is a slight decline. Under REIN, the response was essentially flat, at 10.83, 10.75, and 12.10 μmol g^{-1} FW. The increase in the across-dripline mean from 12.4 to 14.6 μmol g^{-1} FW was therefore driven by XFD alone. The highest proline concentration was recorded for XFD under 60% ETc (18.5 μmol g^{-1} FW), approximately 1.7 times the lowest value observed for REIN under 100% ETc. In conclusion, leaf proline concentration increased with increasing water

deficit under the XFD dripline, indicating exposure to water stress and osmotic adjustment, whereas the response was small under UNIRAM and REIN.

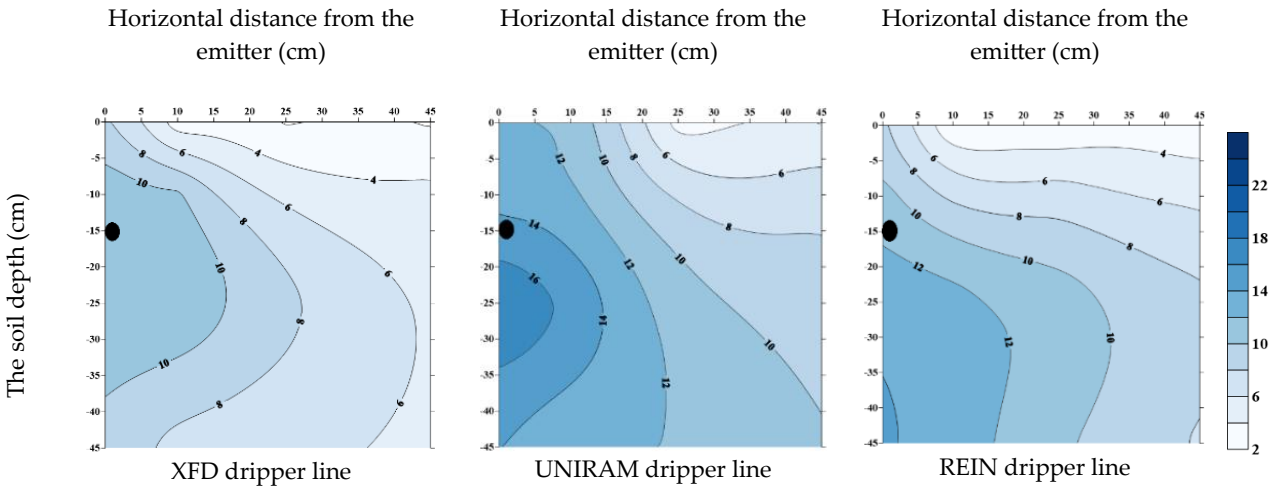


Figure 6. Kriged soil-water distribution maps under SSDI at 60% ETc. The emitter is located at 15 cm.

3.7. Physical Fruit Characteristics

Fruit length, diameter, and individual fruit weight varied among irrigation level × dripline combinations (Figure 7). Across irrigation levels, XFD and UNIRAM generally produced larger fruits than REIN. Fruit length ranged from 13.76 to 14.46 cm with XFD and from 13.02 to 14.30 cm with UNIRAM, compared with 11.50–12.88 cm for REIN (Figure 8A).

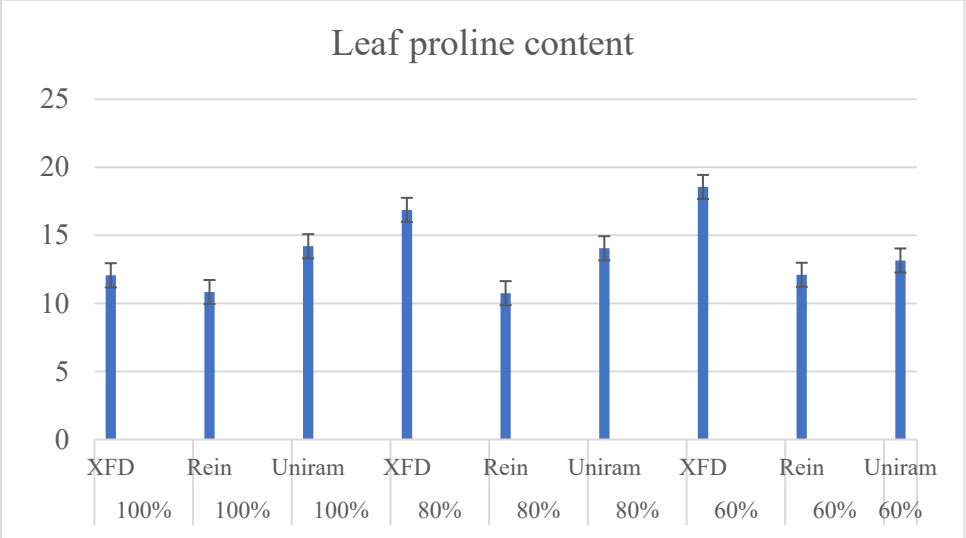


Figure 7. Leaf proline content under different irrigation levels and dripline types (μmol g^{-1} FW).

A similar pattern was observed for fruit diameter (Figure 8B). XFD produced fruit diameters ranging from 27.1 to 30.9 mm, whereas the corresponding ranges were 27.1–29.0 mm for UNIRAM and 26.8–28.0 mm for REIN.

Individual fruit weight also varied among treatment combinations (Figure 8C). The highest value was recorded with XFD under 100% ETc (201.3 g), followed by UNIRAM under 100% ETc (193.7 g). REIN consistently produced the lowest fruit weights across irrigation levels. Fruit weight ranged from 156.1 to 201.3 g for XFD, 157.2 to 193.7 g for

UNIRAM, and 125.3 to 146.4 g for REIN. Overall, fruit size and weight generally decreased as irrigation level was reduced, with the lowest values most frequently observed under REIN.

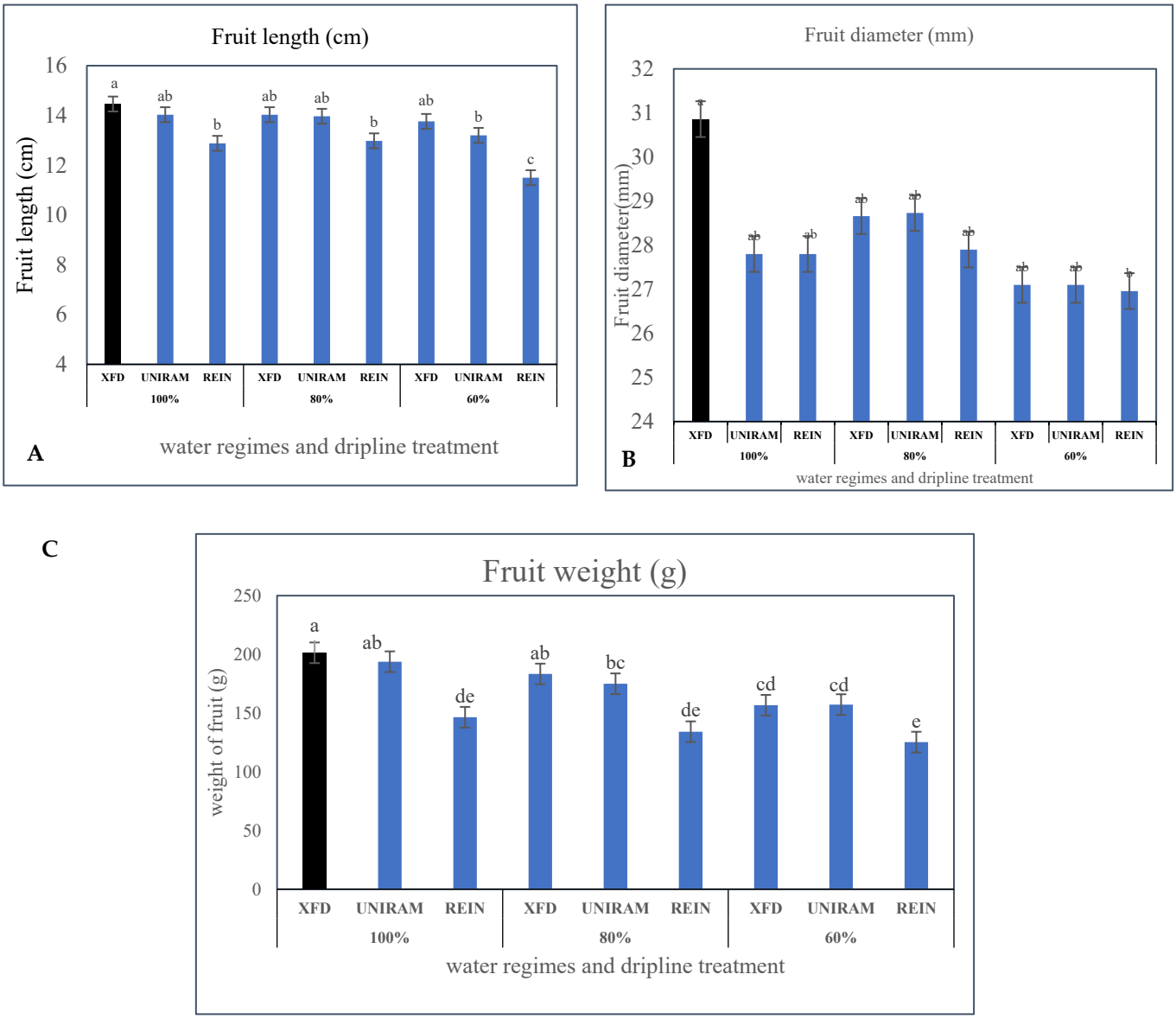


Figure 8. Physical fruit characteristics under different irrigation level × dripline combinations: (**A**) fruit length, (**B**) fruit diameter, and (**C**) fruit weight. Error bars represent the standard deviation of three replicates. The irrigation level × dripline interaction was not statistically significant. Darker blue indicates higher treatment intensity, while lighter blue indicates lower intensity.

3.8. Economic and Water-Reallocation Analysis

The economic outcomes of the irrigation level × dripline combinations are presented in Table 9. Reducing irrigation from 100% ETc to 80% and 60% ETc lowered the amount of irrigation water applied by 18.8% and 37.7%, respectively. For XFD, these water savings were accompanied by yield reductions of 15.6% and 34.7% at 80% and 60% ETc, respectively.

When the saved irrigation water was reallocated while maintaining the same total water budget, the additional irrigated area increased by 23.2% under 80% ETc and 60.4% under 60% ETc. For XFD, water reallocation increased total production by 4.0% under 80%

ETc and 4.8% under 60% ETc relative to full irrigation. The 60% ETc treatment also reduced the water required per unit of production, with the lowest value recorded for XFD × 60% ETc (7.78 m^3 t^{-1}), compared with 17.4 m^3 t^{-1} for REIN × 100% ETc.

Economic performance differed among treatment combinations. Under the water-reallocation scenario, the highest net return was obtained with XFD × 60% ETc, followed by XFD × 80% ETc and XFD × 100% ETc, whereas REIN treatments produced lower net returns. For XFD, net profit increased from approximately 237,046 SAR under 100% ETc to 251,095 SAR under 60% ETc, corresponding to an increase of approximately 5.9%, while the net profit-to-cost ratio increased from 30.8 to 47.0 (Table 9).

The robustness of these economic outcomes to variation in cucumber selling price was further evaluated through sensitivity analysis. Varying the baseline selling price of 3.5 SAR kg^{-1} by ±10%, ±20%, and ±30% affected the magnitude of net profit but did not alter the relative economic ranking of the treatment combinations within the tested price range. XFD × 60% ETc remained the highest-return treatment across all price scenarios, followed by XFD × 80% ETc and UNIRAM × 60% ETc. These results indicate that the relative economic advantage observed for XFD under deficit irrigation was robust within the evaluated range of cucumber prices, although absolute profitability remained sensitive to the assumed selling price.

Table 9. Economic and water-reallocation outcomes of irrigation level × dripline combinations.

	Irrigation Systems	**XFD Dripper Line**			**UNIRAM Dripper Line**			**REIN Dripper Line**		
	Deficit Irrigation Treatment	**100%**	**80%**	**60%**	**100%**	**80%**	**60%**	**100%**	**80%**	**60%**
(1)	Irrigation water applied (m^3)	1451.1	1177.9	904.7	1451.1	1177.9	904.7	1451.1	1177.9	904.7
(2)	Water saved (m^3)	0.0	273.2	546.4	0.0	273.2	546.4	0.0	273.2	546.4
(3)	Water saving (%)	0	18.8	37.7	0.0	18.8	37.7	0.0	18.8	37.7
(4)	Actual yield (t ha^{-1})	111.0	93.7	72.5	104.0	83.5	69.4	83.6	64.3	53.7
(5)	Yield reduction (%)	0.0	−15.6	−34.7	0.0	−19.7	−33.3	0.0	−23.1	−35.8
[6]	Additional irrigable area (%)	0.0	23.2	60.4	0.0	23.2	60.4	0.0	23.2	60.4
(7)	Additional production from reallocated water (t)	0.0	21.7	43.8	0.0	19.4	41.9	0.0	14.9	32.4
(8)	Total production under the fixed water budget (t)	111.0	115.4	116.3	104.0	102.9	111.3	83.6	79.2	86.1
(9)	Postharvest and transport losses (t) ((8) × 10%)	11.1	11.5	11.6	10.4	10.3	11.1	8.4	7.9	8.6
(10)	Remaining production after losses (t) ((8)−(9))	99.9	103.9	104.7	93.6	92.6	100.2	75.2	71.3	77.5
(11)	Graded marketable production (t) ((10) ×70%)	69.9	72.7	73.3	65.5	64.8	70.1	52.7	49.9	54.3
(12)	Non-graded production (t) ((10) ×30%)	30.0	31.2	31.4	28.1	27.8	30.1	22.6	21.4	23.3
(13)	Change in total production (%)	0.0	4.0	4.8	0.0	−1.1	7.0	0.0	−5.2	3.0
[14]	Irrigation and greenhouse installation costs (SAR)	6272.8	5091.5	3910.6	6268.5	5088.06	3908.4	6260.4	5081.0	3902.9
[15]	Other agriculture practices (SAR)	1435.9	1435.9	1435.9	1435.9	1435.9	1435.9	1435.9	1435.9	1435.9
(16)	Original total cost (SAR) ((14) + (15))	7708.7	6527.4	5346.6	7704.4	6524.4	5344.01	7696.3	6517.6	5338.9
(17)	Water required per unit production (m^3 t^{-1}) ((1)/(8))	13.1	10.2	7.8	13.95	11.5	8.1	17.4	14.9	10.5

(18)	Gross revenue from marketable yield (SAR) ((11) × 3.5 × 1000)	244,755.0	254,457.0	256,441.5	229,320.0	226,894.5	245,416.5	184,338.0	174,636.0	189,850.5
(19)	Net profit (SAR) ((18) – ((16))	237,046.3	247,929.6	251,094.9	221,615.6	220,370.1	240,072.5	176,641.7	168,118.4	184,511.6
(20)	Net profit-to-cost ratio ((19)/(16))	30.8	38.0	47.0	28.8	33.8	44.9	23.0	25.8	34.6

Note: A baseline cucumber selling price of 3.5 SAR kg^{-1} (approximately 0.93 USD kg^{-1}) was used to calculate gross revenue from graded marketable production. This value was treated as an analytical baseline rather than as a fixed or nationally representative market price. The net profit-to-cost ratio was calculated as net profit divided by total production cost and is dimensionless. Treatment yields in row (4) are the irrigation level × dripline means reported in Table 6, rounded to one decimal place. Rows (7)–(12) and (18)–(20) refer to total production over the expanded area under the fixed water-budget scenario and are therefore expressed in tonnes rather than per hectare.

The sensitivity analysis showed that variation in cucumber selling price affected the magnitude of net profit but did not alter the relative economic ranking of the treatment combinations within the evaluated price range (Table 10). When the baseline selling price of 3.5 SAR kg^{-1} was varied by ±10%, ±20%, and ±30%, XFD × 60% ETc consistently produced the highest net profit, followed by XFD × 80% ETc and UNIRAM × 60% ETc. For XFD × 60% ETc, net profit ranged from approximately 174,162 SAR at a 30% reduction in selling price to 328,027 SAR at a 30% increase, compared with 251,095 SAR at the baseline price. These results indicate that the relative economic ranking was robust within the tested price range, although the absolute profitability of all treatments remained sensitive to cucumber selling price.

Table 10. Sensitivity analysis of net profit (SAR) for irrigation level × dripline combinations under changes in cucumber selling price.

Dripline	Irrigation Level	−30% 2.45 SAR kg^{-1}	−20% 2.80 SAR kg^{-1}	−10% 3.15 SAR kg^{-1}	Baseline 3.50 SAR kg^{-1}	+10% 3.85 SAR kg^{-1}	+20% 4.20 SAR kg^{-1}	+30% 4.55 SAR kg^{-1}
XFD	100% ETc	163,619.8	188,095.3	212,570.8	237,046.3	261,521.8	285,997.3	310,472.8
	80% ETc	171,592.5	197,038.2	222,483.9	247,929.6	273,375.3	298,821.0	324,266.7
	60% ETc	174,162.4	199,806.6	225,450.8	251,094.9	276,739.1	302,383.2	328,027.4
UNIRAM	100% ETc	152,819.6	175,751.6	198,683.6	221,615.6	244,547.6	267,479.6	290,411.6
	80% ETc	152,301.8	174,991.2	197,680.7	220,370.1	243,059.6	265,749.0	288,438.4
	60% ETc	166,447.5	190,989.2	215,530.8	240,072.5	264,614.1	289,155.8	313,697.4
REIN	100% ETc	121,340.3	139,774.1	158,207.9	176,641.7	195,075.5	213,509.3	231,943.1
	80% ETc	115,727.6	133,191.2	150,654.8	168,118.4	185,582.0	203,045.6	220,509.2
	60% ETc	127,556.4	146,541.5	165,526.6	184,511.6	203,496.7	222,481.7	241,466.8

Note: The baseline cucumber selling price was 3.5 SAR kg^{-1}. Price scenarios represent −30%, −20%, −10%, +10%, +20%, and +30% changes relative to the baseline. Treatment yields and production costs were held constant. Net profit at each price level was recalculated by proportionally adjusting gross revenue relative to the baseline selling price and subtracting the corresponding original total cost. Baseline values in this table correspond to row [19] of Table 9.

Figure 9 illustrates the water-reallocation scenario for the 60% ETc treatment. Under full irrigation, seasonal irrigation depth was 362.76 mm and mean cucumber yield was 99.5 t ha^{-1}. Reducing irrigation to 60% ETc lowered the seasonal irrigation depth to 225.94 mm and yield to 65.1 t ha^{-1}. Reallocating the 37.7% water savings increased the cultivated area from 1.0 to 1.604 ha under the same total water budget, resulting in a total production of 104.4 t, which was 4.9% higher than the full-irrigation baseline. The corresponding value for the XFD dripline alone was an increase of 4.8% (from 111.0 to 116.3 t).

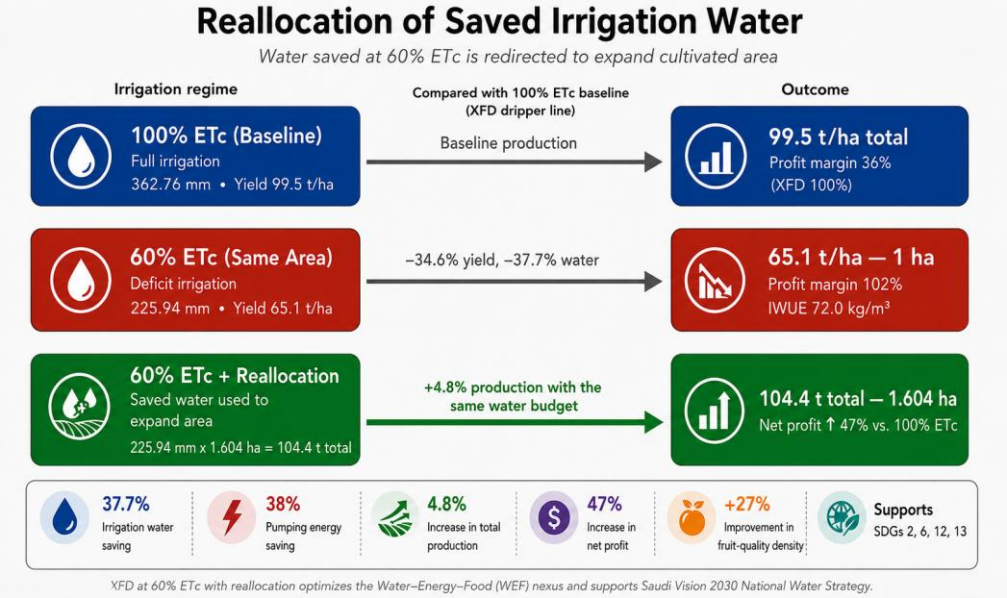


Figure 9. Reallocation arithmetic of the saved irrigation water. Water saved at 60% ETc (37.7%) is reallocated to expand the cultivated area by 60.4%, increasing total production from 99.5 to 104.4 t (+4.9%) while maintaining the same overall irrigation water budget. For the XFD dripline, net profit increased by 5.9% and the net profit-to-cost ratio rose from 30.8 to 47.0**.**

These reallocation outcomes are to be interpreted within the cost boundary defined in Section 2.10.4. Because the incremental capital and operating expenditure required to equip and operate the additional area are not charged against the expanded production, the reported increase in net profit represents an upper bound. The magnitude of the gain would be reduced, and could be eliminated, if the establishment cost of the additional area were internalized over a single season rather than amortized across the economic life of the additional infrastructure.

4. Discussion

The hydraulic performance of the tested driplines differed considerably, particularly in terms of manufacturing variation and discharge stability. XFD and UNIRAM had low discharge exponents (x = 0.034 and 0.047, respectively), indicating a strong pressure-compensating response, whereas the higher exponent of REIN (x = 0.27) was associated with greater discharge variation. This pattern agrees with previous studies showing that emitter design and pressure-compensation characteristics strongly influence discharge uniformity [28,43]. The hydraulic differences observed among the driplines were also reflected in crop performance. Across irrigation levels, the mean yield obtained with REIN was approximately 27% lower than that with XFD. Although the irrigation level × dripline interaction was not significant, the consistent yield ranking among driplines suggests that hydraulic uniformity contributed to maintaining more stable water delivery across the tested irrigation regimes. The three greenhouses were of identical construction and dimensions and were maintained under comparable temperature, relative humidity, and radiation conditions. Nevertheless, identical construction does not by itself eliminate a possible greenhouse effect; this source of variation was therefore accounted for by treating greenhouse as a blocking factor in the split-plot analysis.

The deficit treatments in this study were imposed only after establishment. This design isolates the response of an established crop to water deficit and avoids confounding treatment effects with differential transplant survival or root development. It also means that the reported responses cannot be extrapolated to production systems in which a

deficit is applied from transplanting onward. Early water deficit would be expected to influence root architecture, canopy expansion, and the timing of flowering, and these effects would in turn modify both the yield response and the water-use efficiency reported here. Evaluation of deficit imposition during establishment is therefore identified as a direction for future work.

The spatial distribution of SWC differed among the three driplines, indicating that emitter characteristics influenced soil-water redistribution within the wetted zone. The larger wetted area observed under 100% ETc, in both the vertical and horizontal directions, was mainly associated with the greater volume of water applied. Goldberg et al. [44] similarly reported that horizontal water movement and the final width of the wetted zone along a dripline depend on the amount of water applied. In sandy soils, vertical water movement generally exceeds lateral redistribution, which emphasizes the importance of appropriate emitter spacing in SSDI systems [45,46]. The lower SWC observed near the soil surface may also be related to evaporation and subsequent redistribution of water within the soil profile [47].

Localized SWC values under REIN exceeded the measured field-capacity range, particularly at 100% and 80% ETc, whereas the moisture content under XFD and UNIRAM remained closer to field capacity at locations farther from the emitter. This difference may be associated with the greater discharge variation of REIN and the more uniform water application achieved by XFD and UNIRAM. Previous studies have also reported differences in gravimetric SWC between directions parallel and perpendicular to drip laterals [48,49]. At 60% ETc, lower SWC values were observed in the deeper soil layers, indicating more limited downward water movement than under the higher irrigation levels. Similar responses under reduced irrigation have been associated with changes in water movement and retention within the root zone [50].

The decline in soil water content with increasing horizontal distance from the emitter reflects the balance between gravitational and capillary forces in a coarse-textured profile. Water enters the soil at a point source, so the applied volume per unit soil volume decreases with radial distance from that point. In a profile containing 88.4 to 95.0% sand, the pore system is coarse. Water therefore moves preferentially downward under gravity rather than outward under capillary attraction, producing a wetted zone deeper than it is wide. After the wetting front has passed, further lateral redistribution towards drier soil requires flow through progressively less conductive material, so lateral equalization is slow and the gradient established during application persists until the following irrigation.

This behavior has two consequences relevant to system design. First, emitter spacing is a critical variable in subsurface systems installed in sandy soils, because lateral overlap between adjacent emitters cannot be relied upon to generate a continuous wetted strip. Second, it accounts for the observation that soil water content was generally lower in the upper 0–15 cm layer and increased below 30 cm, since water applied at 0.15 m depth drains downward more readily than it moves upward against gravity.

Crop water uptake is closely related to root distribution and the availability of soil water within the active root zone [51]. Therefore, the smaller wetted zone and lower SWC observed under deficit irrigation may have restricted the volume of soil from which roots could readily extract water. Overall, the soil-water distribution patterns were consistent with the lower water availability observed under 60% and 80% ETc relative to full irrigation. However, the 80% ETc treatment maintained a comparatively wider wetted root-zone profile than 60% ETc, which may partly explain its more moderate yield reduction.

Under severe deficit irrigation (60% ETc), the wetted soil volume became smaller and soil water was more concentrated around the emitters. Differences among the driplines were also more apparent at this irrigation level. XFD maintained a relatively uniform

wetting pattern within the main root-zone depth, whereas UNIRAM showed greater spatial variation in SWC. The moisture pattern under REIN was more irregular, with greater vertical concentration and less lateral spread than those observed with XFD. These differences were consistent with the hydraulic performance of the tested driplines, particularly their discharge variation and uniformity. Under limited water application, non-uniform emitter discharge may become more evident in the resulting soil-water distribution because a smaller volume of water is available for redistribution within the soil profile. Thus, the more uniform wetting pattern observed with XFD may have contributed to maintaining water availability within a larger portion of the active root zone under 60% ETc.

Deficit irrigation reduced cucumber yield, with larger reductions observed as the amount of applied water decreased. This response agrees with the findings of Ayas and Demirtas [52] and Tüzel et al. [53], who reported significant yield reductions in cucumber under decreasing irrigation supply. Inadequate soil-water availability can restrict crop growth and fruit production, whereas excessive irrigation may also adversely affect yield [54]. The strong response of cucumber yield to irrigation amount has been widely reported [55].

Differences in yield among the tested driplines may also be related to their hydraulic performance and the resulting soil-water distribution. Variability in emitter discharge along a drip lateral can contribute to spatial differences in plant growth and biomass production [56]. In the present study, REIN had the highest manufacturer's coefficient of variation (Cv = 0.077) and discharge variation (Q_{var} = 14.7%), together with a less uniform soil-water distribution pattern. These hydraulic characteristics may partly explain the lower yield obtained with REIN compared with XFD and UNIRAM [57]. In contrast, the more uniform wetting patterns observed with XFD and UNIRAM may have supported a more consistent supply of water within the active root zone.

The cucumber yields obtained in this study were lower than the range reported by Alomran and Luki [20], who recorded total yields of 90–150 t ha^{-1} during a 140-day greenhouse cropping season in Riyadh. The shorter cropping period used in the present experiment (90 days) may partly account for this difference. Nevertheless, the treatment yields, which ranged from approximately 53 to 110 t ha^{-1}, were comparable to the average cucumber yield reported by Aly et al. [58]. The reduction in yield under deficit irrigation is attributable to the quantity of water applied rather than to its placement or its uniformity of delivery. Delivery was not limiting, since XFD and UNIRAM achieved uniformity coefficients of 98.3% and 97.8%, classified as excellent, yet yield declined under both driplines as irrigation was reduced. Placement was likewise appropriate, since the driplines were installed at 0.15 m depth with emitters spaced 0.30 m apart and the kriged maps confirm that the wetted zone remained centred within the effective root zone at all irrigation levels. The operative constraint was the contraction of the wetted volume itself, from approximately 35 × 35 cm under 100% ETc to 28 × 30 cm under 80% ETc and 22 × 25 cm under 60% ETc.

The shallow root system of cucumber makes the crop particularly sensitive to this contraction. A deeper-rooted species could partly compensate by extracting water stored below the wetted bulb, whereas cucumber is largely confined to it. The reduced volume of accessible water lowers plant water potential and stomatal conductance, and consequently carbon assimilation. In an indeterminate, continuously fruiting crop, this constrains both the number of fruits retained and the growth of individual fruits, and both responses were observed. Fruit number per plant declined from 23.2 under full irrigation to 17.1 at 60% ETc, and mean individual fruit weight under XFD declined from 201.3 to 156.1 g over the same range.

Although yield declined under deficit irrigation, water-use efficiency responded differently. The highest IWUE and WUE values were recorded at 60% ETc, in agreement

with previous studies reporting improved water productivity as irrigation supply decreased [59,60]. This finding shows that the treatment producing the highest yield was not necessarily the most efficient in terms of water use. However, the higher water productivity at 60% ETc should be considered together with the associated yield reduction when selecting an irrigation strategy.

Proline content increased under deficit irrigation, with the highest values recorded under the XFD dripline at 60% ETc. This response is consistent with osmotic adjustment following exposure to water deficit. Proline accumulation is a marker of plant water status and does not, by itself, demonstrate improved drought tolerance or explain the differences in yield among treatments. Indeed, the concurrent reduction in yield suggests that the observed accumulation primarily reflected greater exposure to water stress rather than improved crop productivity. Proline increased progressively with decreasing irrigation under XFD, remained approximately constant under UNIRAM, and varied little under REIN. The greater accumulation observed under XFD could be associated with its more uniform soil-water distribution, which may have imposed a more spatially consistent water-deficit condition within the root zone; however, this relationship was not directly tested in the present study. Under water stress, proline can contribute to osmotic adjustment, reactive oxygen species (ROS) scavenging, and membrane stabilization [61,62]. Thus, the high proline concentration under XFD × 60% ETc provides physiological evidence of crop exposure to water deficit under relatively uniform soil-water conditions. It should be emphasized, however, that proline was measured in fully expanded leaves and was used solely as an indicator of plant water-stress response. Because proline was not measured in the fruits, the present results provide no evidence of changes in the proline content, nutritional composition, or safety of the edible portion.

Fruit physical characteristics were also significantly affected by irrigation level. The 100% ETc treatment produced the highest values of fruit length, diameter, and weight compared with the 80% and 60% ETc treatments. Similar results were reported by Sahin et al. [63], who found that increasing irrigation water application improved cucumber fruit length, diameter, and weight. The greater fruit diameter observed under full irrigation also agrees with Ayas and Demirtas [52], who reported higher fruit diameter under 100% irrigation than under deficit-irrigation treatments. Likewise, mean fruit weight was higher under the 100% ETc treatment and declined with increasing water deficit. Significant positive correlations ($p < 0.01$) between mean fruit weight and plant water consumption, and between mean fruit weight and yield, have previously been reported, indicating that greater water availability promotes the development of heavier cucumber fruits [64]. Similarly, Mannini [27] reported that increased irrigation water application and crop water consumption enhanced mean fruit weight and consequently contributed to higher yield.

Deficit irrigation also affected the measured physical attributes of cucumber fruits. Fruit expansion is strongly dependent on cell turgor, and reduced root-zone water availability can restrict fruit growth. This is consistent with the reductions in fruit length, diameter, and individual fruit weight observed as irrigation decreased in the present study. These responses may have implications for marketable quality because fruit size and appearance are important commercial attributes of cucumber. More broadly, preharvest water availability can influence fruit dry matter, firmness, biochemical composition, and postharvest behaviour through changes in plant water status, assimilate partitioning, and stress responses. However, these responses are strongly dependent on crop species, greenhouse environment, and the severity and timing of water limitation [65]. Recent evidence emphasizes that cucumber fruit quality and shelf life are particularly sensitive to preharvest water status and epidermal characteristics, highlighting the importance of considering irrigation management not only in relation to yield but also to postharvest

performance [65]. In the present study, dry matter content, firmness, biochemical composition, and postharvest shelf life were not measured; therefore, no direct conclusions can be drawn regarding these attributes. Future studies should combine deficit-irrigation treatments with comprehensive fruit-quality and postharvest assessments to determine whether the water savings achieved here can be obtained without compromising marketability or storage performance.

The results suggest that the choice of deficit-irrigation strategy depends on the resource constraint considered. Under 80% ETc, XFD retained approximately 84.5% of the yield obtained under full irrigation while reducing irrigation water use by 18.8%. This response is broadly consistent with the meta-analysis of Singh et al. [26], which showed relatively small average yield reductions in vegetable crops when irrigation was maintained above 80% of full irrigation. Parkash et al. [66] also reported that cucumber yield under 80% ETc was statistically comparable to that under full irrigation in greenhouse production. In the present study, the 80% ETc treatment therefore provided a compromise between water saving and yield maintenance, particularly where the cultivated area is limited.

A different outcome was observed under 60% ETc. Although mean yield decreased by approximately 35%, this treatment produced the highest IWUE, reaching 72.0 kg m^{-3} across driplines and 80.1 kg m^{-3} with XFD. The economic implications changed when the water saved under deficit irrigation was reallocated within a fixed water budget. Reallocating the 37.7% water saving under 60% ETc increased the potentially irrigated area by 60.4% and, for XFD, increased total production by 4.8% and net profit by approximately 5.9% relative to full irrigation, while the net profit-to-cost ratio rose from 30.8 to 47.0. Thus, 60% ETc may be economically attractive where irrigation water is the principal limiting resource and additional land is available for cultivation.

The economic implications of deficit irrigation change when conserved water is considered a resource that could potentially be reallocated under a fixed water budget. Under the assumptions defined in Section 2.9, reallocating the 37.7% water saving achieved at 60% ETc would theoretically allow the irrigated area to increase by 60.4%. For XFD, this scenario would increase total production by approximately 4.8% relative to full irrigation. The corresponding calculated net profit increased from 237,046.3 to 251,094.9 SAR, equivalent to approximately 5.9%, while the net profit-to-cost ratio increased from 30.8 to 47.0. These outcomes are conditional on several assumptions that may not hold simultaneously in commercial greenhouse production. Expansion would require additional capital for greenhouse structures and irrigation infrastructure, sufficient land, proportional increases in labour and energy inputs, and a market capable of absorbing the additional production at the assumed price. The reallocation analysis should therefore be interpreted as a hypothetical management scenario illustrating the potential value of conserved water under idealized conditions, rather than as a direct economic benefit to growers. Moreover, expansion of the irrigated area could offset field-level water savings at a broader scale, illustrating the irrigation-efficiency paradox whereby improved water productivity does not necessarily translate into reduced aggregate water abstraction.

These results should, however, be interpreted in the context of the irrigation-efficiency paradox discussed by Grafton et al. [29] and Pérez-Blanco et al. [67]. Improvements in field-scale water efficiency do not necessarily reduce total water abstraction if the saved water is used to expand the irrigated area. The reallocation scenario evaluated in this study assumes a fixed total water budget; therefore, the increase in cultivated area represents an alternative use of the same irrigation-water allocation rather than an increase in total abstraction. Within such a constraint, reallocation of saved water could increase agricultural production and farm returns without increasing the initial irrigation-water budget.

Taken together, the results show that combining high-uniformity subsurface drip irrigation with deficit irrigation can improve the use of limited irrigation water under arid conditions. The XFD dripline maintained more uniform water distribution and higher crop performance than the other tested driplines, while the 60% ETc treatment achieved the highest water-use efficiency. When the water saved at 60% ETc was reallocated under a fixed water budget, the additional irrigated area increased total production and farm profitability despite the lower yield per unit area.

The findings of the present study also have relevance to the broader challenge of climate change adaptation in water-limited greenhouse horticulture. Although the quantitative responses reported here are specific to greenhouse cucumber grown under the experimental conditions of central Saudi Arabia, increasing temperature, atmospheric evaporative demand, and pressure on irrigation-water resources are becoming important constraints in many arid and semi-arid production regions [68]. Under these conditions, maintaining crop productivity with a limited water supply will require irrigation strategies that improve the precision and uniformity of water delivery while avoiding levels of deficit that impose excessive physiological and yield penalties. The present results illustrate this trade-off: moderate deficit irrigation reduced water use while maintaining a greater proportion of yield, whereas the more severe deficit increased water-use efficiency but imposed a substantially larger yield penalty.

Climate adaptation in protected horticulture, however, cannot rely on irrigation management alone. Integrated strategies combining efficient irrigation and improved resource-use efficiency with crop- and greenhouse-level adaptation measures, including cultivar selection, grafting, and canopy and microclimate management, are increasingly important for maintaining productivity under warmer and more water-limited conditions [68]. Within such integrated strategies, hydraulic uniformity remains particularly relevant because spatially uneven water application may increase variability in root-zone water availability when the irrigation supply is restricted. Nevertheless, the interaction among increasing evaporative demand, irrigation uniformity, crop physiology, and deficit severity was not directly evaluated in the present experiment. Multi-season studies incorporating greenhouse microclimate measurements and contrasting climatic conditions are therefore needed to determine whether irrigation thresholds established under current conditions require adjustment as evaporative demand increases.

The main contribution of this study is the combined evaluation of dripline hydraulics, soil-water distribution, crop response, and economic outcomes within the same experimental framework. The results indicate that the benefits of deficit irrigation depend not only on the amount of water saved but also on emitter performance and how the saved water is subsequently used. This integrated approach may support irrigation-management decisions in water-limited agricultural systems and is consistent with the water-efficiency and sustainable agricultural objectives of Saudi Vision 2030 and the National Water Strategy.

Mechanistic Interpretation: From Emitter Hydraulics to Yield Formation

The observed responses can be interpreted within a mechanistic framework linking dripline hydraulics, soil-water distribution, plant water status, and yield formation. Emitter design first determines the uniformity of water application. XFD and UNIRAM are pressure-compensating driplines with discharge exponents of 0.034 and 0.047, respectively. In the relationship q = kH^x, an exponent approaching zero indicates relatively low sensitivity of emitter discharge to changes in pressure head. In contrast, REIN had a higher discharge exponent (0.27), indicating greater sensitivity to pressure variation. REIN also showed a higher coefficient of manufacturing variation (Cv = 0.077) and discharge variation (Qvar = 14.7%) than XFD (Cv = 0.021; Qvar = 5.5%) and UNIRAM (Cv = 0.026; Qvar =

7.1%). These hydraulic differences provide a plausible explanation for the greater spatial variation in soil water observed under REIN and the more uniform patterns under XFD and UNIRAM. In the predominantly sandy experimental soil, limited lateral redistribution would be less able to compensate for differences in the volume delivered by neighbouring emitters [14]. Consequently, local differences in emitter discharge could remain evident in the resulting wetting pattern, contributing to the locally higher soil-water contents observed under REIN. The broader implication of this comparison therefore lies in hydraulic performance rather than product identity: SSDI systems with lower pressure sensitivity and discharge variation are expected to provide more spatially consistent water application, although the resulting soil-water distribution will also depend on soil hydraulic properties and field operating conditions.

The decrease in soil water content with increasing horizontal distance from the emitter can be explained by the same soil hydraulic characteristics. Water is introduced locally at each buried emitter and subsequently redistributes through the surrounding soil. In the predominantly sandy profile, gravitational drainage is relatively strong, whereas lateral capillary redistribution is limited [18]. Consequently, water tends to move preferentially downward from the emitter, while progressively less water reaches soil located farther away in the horizontal direction. This produces the observed gradient of higher soil water content near the emitter and lower values with increasing horizontal distance. The same process also helps explain the greater water contents observed at deeper positions in the soil profile.

The resulting geometry and persistence of the wetted zone can, in turn, influence the volume of soil from which roots can extract readily available water. Root water uptake under drip irrigation depends on the spatial relationship among root distribution, soil-water availability, and the wetted volume [45,52]. The decline in cucumber yield with decreasing irrigation is therefore more consistently explained by a reduction in readily available root-zone water than by inadequate placement of the driplines. The driplines were installed at a depth of 0.15 m with emitters spaced 0.30 m apart, and the soil-water maps showed that water remained distributed around the emitter position under all irrigation levels. Moreover, yield declined with decreasing irrigation even under XFD and UNIRAM, which exhibited high discharge uniformity, indicating that hydraulic non-uniformity alone cannot explain the response to irrigation level. Instead, the wetted zone progressively contracted from approximately 35 × 35 cm under 100% ETc to 28 × 30 cm under 80% ETc and 22 × 25 cm under 60% ETc. For a relatively shallow-rooted crop such as cucumber, this contraction would reduce the soil volume from which readily available water can be extracted and increase the likelihood of transient root-zone water deficits between irrigation events. Under such conditions, plants typically regulate water loss through changes in stomatal behaviour, with consequent limitations on transpiration and carbon assimilation; however, stomatal conductance, leaf water potential, and photosynthetic rate were not directly measured in the present experiment [48,69].

The observed proline response provides complementary physiological evidence of plant exposure to water deficit. Proline can contribute to osmotic adjustment, membrane stabilization, and protection against oxidative stress under water-limited conditions [63,64]. The highest leaf proline concentration (18.55 μmol g^{-1} FW) occurred under XFD at 60% ETc. As discussed above, this accumulation should be interpreted as a stress-response indicator rather than direct evidence of enhanced drought tolerance or maintained carbon assimilation.

These hydraulic and physiological responses provide a plausible framework for interpreting the observed changes in reproductive performance. Restricted water availability and associated limitations on carbon assimilation can constrain fruit set and fruit growth in cucumber [48,69]. In the present study, fruit number per plant declined from

23.2 under full irrigation to 17.1 at 60% ETc, while mean individual fruit weight under XFD decreased from 201.3 to 156.1 g. The simultaneous reductions in fruit number and individual fruit growth were therefore consistent with the observed decline in marketable yield under severe deficit irrigation. Nevertheless, root distribution, plant hydraulic conductance, stomatal conductance, photosynthetic carbon assimilation, and assimilate partitioning were not directly quantified. The relationships proposed here should therefore be regarded as a mechanistic interpretation consistent with the measured hydraulic, soil-water, physiological, and yield responses rather than as a directly demonstrated causal pathway. Future studies incorporating root-system characterization, leaf water potential, gas exchange, and carbon-allocation measurements would allow these mechanisms to be tested directly.

5. Practical Implications, Commercialization and Adoption

5.1. Practical Implications and Significance

The results of this study have direct implications for irrigation management in water-limited greenhouse production. The superior hydraulic performance of XFD, together with its more uniform soil-water distribution and higher crop performance, shows the importance of dripline selection when deficit irrigation is applied. Irrigation scheduling alone may therefore be insufficient to achieve the expected water savings if emitter discharge is not sufficiently uniform. For sandy soils, where water redistribution is limited by rapid vertical movement, the hydraulic characteristics of the dripline become particularly important for maintaining water availability within the active root zone.

The water-reallocation analysis also provides a practical perspective on the use of water saved through deficit irrigation. Under a fixed water budget, applying 60% ETc reduced irrigation water use by 37.7% and allowed the potentially irrigated area to increase by 60.4%. For XFD, this scenario increased total production by 4.8% and net profit by approximately 5.9% relative to full irrigation, while the net profit-to-cost ratio rose from 30.8 to 47.0. These results indicate that the value of deficit irrigation depends not only on field-scale water productivity but also on how the saved water is managed. Where additional land is available and total water use remains constrained, reallocating saved water may partly offset the yield reduction per unit area and improve overall farm returns.

From a practical standpoint, the results support the use of high-uniformity SSDI combined with deficit irrigation according to the main resource constraint. An irrigation level of 80% ETc may be more suitable where cultivated area is limited and maintaining yield per unit area is a priority, whereas 60% ETc combined with water reallocation may offer greater economic benefits where water is the principal constraint and additional land is available. These findings are relevant to efforts to improve agricultural water-use efficiency and are consistent with the water-conservation objectives of Saudi Vision 2030 and the National Water Strategy.

5.2. Cost, Maintenance, and Adoption Considerations

Practical adoption of subsurface drip irrigation depends on factors beyond agronomic performance. The driplines evaluated in this study cost 0.23, 0.22, and 0.15 USD m^{-1} for XFD, UNIRAM, and REIN, respectively. Thus, XFD had a purchase cost approximately 53% higher than REIN, but it also produced substantially higher mean yield and irrigation water-use efficiency under the conditions of this study. Over the assumed eight-year economic life of the system, the initial dripline cost should therefore be considered together with its hydraulic performance and potential effects on crop productivity rather than used as the sole criterion for system selection. Trenching and lateral installation added

approximately 0.23 USD m^{-1}, making installation an additional consideration when evaluating the initial investment in SSDI [42].

Maintenance is particularly important in SSDI because buried emitters cannot be visually inspected during normal operation. Adequate filtration, periodic flushing, monitoring of system pressure and discharge, and appropriate water-quality management are therefore important for limiting clogging and maintaining hydraulic performance [12,43]. Root intrusion and soil entry around emitter outlets may present additional maintenance concerns in buried systems [12,43]. Burial can protect laterals from ultraviolet exposure and some forms of mechanical damage, but locating faults and replacing buried components can be more difficult than in surface drip systems [12,43]. Reliable pressure regulation and appropriate irrigation scheduling are also important for maintaining the expected hydraulic and water-saving performance of the system [27,43].

For small- and medium-scale greenhouse growers, adoption will therefore depend on whether the expected water and productivity benefits justify the additional initial investment and maintenance requirements. Economic assessments of irrigation technologies should account for investment, operating, and system-life considerations rather than initial equipment cost alone [42]. Access to technical support, appropriate filtration and maintenance facilities, and suitable financing mechanisms may facilitate adoption. However, grower adoption, financing constraints, maintenance costs over the system life, and long-term durability were not directly evaluated in the present study. These considerations should therefore be interpreted as practical implications of the experimental and economic results rather than as demonstrated adoption outcomes. Future multi-season studies should include life-cycle cost analysis, field monitoring of clogging and system durability, and grower-scale evaluations to determine the commercial feasibility of SSDI under different farm sizes and management capacities.

Management option for greenhouse cucumber production in arid environments. The proposed approach may assist growers and irrigation managers in selecting irrigation strategies

5.3. Future Water-Supply Pathways for Water-Limited Greenhouse Production

Improving irrigation efficiency can reduce agricultural water demand, but long-term water sustainability in arid regions also requires consideration of alternative and supplementary water sources. In the present study, regulated deficit irrigation reduced seasonal irrigation requirements by 18.8% and 37.7% under 80% and 60% ETc, respectively. Such demand-side savings could reduce the volume of water that must be supplied from conventional or alternative sources and may therefore facilitate the integration of water-saving irrigation with broader water-resource strategies.

Several emerging approaches may have potential under Saudi conditions. Seawater-based controlled-environment systems, such as the Sahara Forest concept, integrate saline water, renewable energy, and protected horticulture and may be particularly relevant to the Red Sea and Arabian Gulf coastal regions, where seawater conveyance requirements are comparatively low [69]. In inland areas, atmospheric water harvesting may be constrained by low ambient humidity; however, recovering water vapour generated by crop transpiration within closed or semi-closed greenhouses could provide a more favourable opportunity for water recycling [70–72].

Treated wastewater and brackish groundwater also represent potential supplementary sources for irrigation in water-limited regions. Their use with SSDI may reduce direct contact between irrigation water and the crop canopy and limit surface evaporation, although salinity management, adequate filtration, and emitter clogging become increasingly important when marginal-quality water is used. Emerging water-conditioning approaches, including electro-agric and magnetic-field treatments, have also been proposed

for improving the usability of marginal water, but their effectiveness and economic feasibility under subsurface drip irrigation require further experimental evaluation [73]. Managed aquifer recharge using treated wastewater or captured runoff may provide an additional longer-term option for supporting groundwater-resource sustainability [74].

These technologies were not evaluated experimentally in the present study. They are therefore considered here as potential future pathways through which the demand-side water savings achieved with high-uniformity SSDI and regulated deficit irrigation could be integrated into a broader water-management strategy for arid and semi-arid agriculture.

6. Limitations of the Study

Soil organic matter was not characterized in the present study, which should be considered when interpreting the soil-water and plant-response results. This limitation is particularly relevant to the predominantly sandy experimental soil, where organic matter can improve water and nutrient retention and may slow water movement below the effective root zone. Such changes could influence the geometry and persistence of the wetted zone and, consequently, root-zone water availability under deficit SSDI. This consideration is especially important in the present experiment because the coarse-textured soil promoted relatively rapid vertical redistribution, while the different driplines produced distinct wetting patterns. Improved root-zone water retention associated with higher native organic matter content or organic amendments could also modify the intensity of crop water stress and, potentially, the associated proline response. The physiological responses observed in this study should therefore be interpreted within the specific soil conditions under which the experiment was conducted. Future studies should quantify soil organic matter and examine its interaction with dripline hydraulic performance, soil-water redistribution, and plant water-stress responses under deficit irrigation.

Crop evapotranspiration in this study was estimated from pan evaporation. Under protected cultivation, incoming solar radiation is attenuated by the greenhouse cover, air movement is strongly reduced, and vapor pressure deficit is influenced by both the enclosed environment and crop transpiration. Air temperature and relative humidity alone therefore do not fully characterize greenhouse evaporative demand. Because the same ETo estimate was used to derive all irrigation treatments, any systematic bias in the pan-based estimate would have affected the absolute irrigation depths in a similar manner across treatments, while preserving the intended relative differences among irrigation levels. Nevertheless, the absolute irrigation depths reported here should be interpreted with this limitation in mind. Future studies should employ greenhouse-calibrated radiation-based or combination methods supported by direct measurements of solar radiation and vapor pressure deficit within the greenhouse.

The soil-water distribution maps presented in this study represent the redistributed wetting pattern measured 24 h after irrigation. Because irrigation was applied daily, this sampling time corresponded to the condition immediately preceding the subsequent irrigation event and therefore represented the driest measured state of the irrigation cycle. Although this provides a conservative characterization of the wetted zone, a single spatial assessment cannot describe soil-water depletion and redistribution dynamics between irrigation events or short-term variations in root-zone water availability. Future studies should therefore incorporate continuous soil-moisture monitoring at multiple depths and lateral distances from the emitter to characterize the temporal as well as spatial dynamics of water within the root zone.

The hydraulic indices reported in this study were determined under controlled laboratory conditions and were not verified by direct in-situ discharge measurements after installation. Actual emitter performance under greenhouse conditions may be influenced

by water temperature, pressure variation along the laterals, emitter clogging, and installation-related effects such as soil or root intrusion. These factors may affect pressure-compensating and non-compensating emitters differently and could alter the discharge characteristics observed under laboratory conditions. Although the soil-water distribution patterns were generally consistent with the laboratory hydraulic ranking, particularly the greater spatial variability associated with REIN, these patterns provide only indirect evidence and cannot substitute for direct field measurement of emitter discharge. Future studies should therefore monitor in-situ emitter discharge, pressure variation, and clogging development over multiple growing seasons to determine whether the laboratory hydraulic characteristics are maintained under operational SSDI conditions.

The present study evaluated a single cucumber cultivar during a single growing season, which limits the transferability of the quantitative crop-response results to other genetic backgrounds. Cucumber cultivars can differ in rooting characteristics, transpiration and stomatal responses to water deficit, growth and fruiting patterns, and physiological responses to water stress, resulting in cultivar-dependent responses to deficit irrigation Parkash et al. [66]. Consequently, the yield response, water-use efficiency, fruit characteristics, and physiological responses reported here should be interpreted as specific to the cultivar and growing conditions evaluated. In contrast, the hydraulic characteristics of the driplines and their influence on soil-water distribution are expected to be less cultivar-dependent, although their interaction with crop root distribution may still affect actual root-zone water availability. Future studies should therefore evaluate multiple cucumber cultivars across growing seasons to determine the robustness of the irrigation recommendations and to identify cultivar × irrigation interactions under deficit SSDI.

The applicability of the present findings is also bounded by crop species, soil properties, and growing environment. The hydraulic characteristics of the evaluated driplines are system-specific, whereas their effects on root-zone water availability and crop performance depend on interactions among emitter discharge, soil hydraulic properties, root distribution, and crop water uptake [18,52]. Consequently, the yield response to deficit irrigation, water-use efficiency, fruit characteristics, and proline response observed for cucumber should not be extrapolated directly to other greenhouse crops with different rooting patterns, transpiration characteristics, growth cycles, or harvest strategies. The soil-water distribution results are also conditional on the predominantly sandy experimental profile, which contained 88.4–95.0% sand and promoted relatively rapid vertical redistribution. Finer-textured soils may produce different wetting geometries because of greater lateral water redistribution. Accordingly, the quantitative conclusions of this study are most directly applicable to greenhouse cucumber grown in predominantly sandy soil under the arid conditions evaluated here, and their extension to other crop species, soil textures, or growing environments requires independent validation.

7. Conclusions and Recommendations

This study demonstrated that the response of greenhouse cucumber to deficit irrigation depended not only on the amount of water applied but also on the hydraulic performance of the subsurface dripline. The high-uniformity (XFD), pressure-compensating dripline provided more uniform soil-water distribution and consistently improved crop and water-use performance compared with UNIRAM and REIN. Moderate deficit irrigation at 80% ETc provided a practical balance between water saving and yield maintenance, whereas 60% ETc achieved the highest water-use efficiency but was associated with a greater reduction in yield.

The economic value of deficit irrigation changed when the saved irrigation water was considered as a resource that could be reallocated under a fixed water budget. Under this scenario, the lower yield per unit area at 60% ETc could be partly offset by expanding the

cultivated area, resulting in higher overall production and farm returns. This finding emphasizes that the practical benefit of water-saving irrigation depends not only on field-level irrigation performance but also on how the conserved water is subsequently managed. Overall, combining high-uniformity SSDI with an irrigation strategy selected according to the principal resource constraint can improve water productivity and economic performance in arid greenhouse production. Under the cultivar and experimental conditions evaluated, the results support the use of 80% ETc where maintaining yield per unit area is a priority, while a more severe deficit combined with controlled water reallocation may be considered where water is the main limiting resource and additional cultivated land is available.

The present study evaluated a single cucumber cultivar during a single growing season, which limits the transferability of the quantitative crop-response results to other cultivars and production conditions. Consequently, the yield response, water-use efficiency, fruit characteristics, and physiological responses reported here should be interpreted within the specific cultivar and growing conditions evaluated. The hydraulic characteristics of the driplines are expected to be more transferable than the crop-response findings, although their effects on root-zone water availability may still interact with crop rooting and water-uptake patterns. Future studies should evaluate multiple cucumber cultivars across growing seasons and contrasting soil and environmental conditions to validate the irrigation recommendations and identify cultivar × irrigation interactions under deficit SSDI. Long-term studies should also assess SSDI performance, emitter clogging, system durability, and the economic feasibility of water-reallocation strategies under commercial greenhouse conditions.

Author Contributions: Conceptualization, A.M.E.-F. and M.A.M.; methodology, A.M.E.-F.; software, M.A.M.; validation, A.M.E.-F., A.E.-S. and M.A.M.; formal analysis, A.M.E.-F.; investigation, A.M.E.-F.; resources, M.A.M.; data curation A.M.E.-F.; writing—original draft preparation, A.M.E.-F.; writing—review and editing, A.E.-S.; visualization, A.M.E.-F. and M.A.M.; supervision, M.A.M.; project administration, A.E.-S.; funding acquisition, A.M.E.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ongoing Research Funding Program (ORF-2026-2197), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data that support the findings of this study are available from the corresponding author.

Acknowledgments: The authors would like to extend their sincere appreciation to the Ongoing Research Funding Program (ORF-2026-2197), King Saud University, Riyadh, Saudi Arabia..

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
SSDI	Subsurface drip irrigation
DI	Deficit irrigation
RDI	Regulated deficit irrigation
ETc	Crop evapotranspiration
ETo	Reference evapotranspiration

SWC	Soil water content
IWUE	Irrigation water-use efficiency
WUE	Water-use efficiency
IWA	Irrigation water applied
FC	Field capacity
PWP	Permanent wilting point
CV/C_v	Coefficient of variation
UC	Christiansen's uniformity coefficient
KSA	Kingdom of Saudi Arabia
MEWA	Ministry of Environment, Water and Agriculture
PC	Pressure compensating
ASABE	American Society of Agricultural and Biological Engineers
ROS	Reactive oxygen species
ECw	Electrical conductivity of irrigation water
SAR	Sodium adsorption ratio
Kc	Crop coefficient
Kp	Pan coefficient
LSD	Least significant difference

References

1. Wutich, A. Water insecurity: An agenda for research and call to action for human biology. *Am. J. Hum. Biol.* **2020**, *32*, e23345.
2. Ismail, S.M.; Al-Qurashi, A.D.; Awad, M.A. Optimization of irrigation water use, yield, and quality of'NABBUT-SAIF'date palm under dry land conditions. *Irrig. Drain.* **2014**, *63*, 29–37.
3. Odnoletkova, N.; Patzek, T.W. Water resources in Saudi Arabia: Trends in rainfall, water consumption, and analysis of agricultural water footprint. *Npj Sustain. Agric.* **2023**, *1*, 7.
4. Chowdhury, S.; Al-Zahrani, M. Implications of climate change on water resources in Saudi Arabia. *Arab. J. Sci. Eng.* **2013**, *38*, 1959–1971.
5. Flörke, M.; Kynast, E.; Bärlund, I.; Eisner, S.; Wimmer, F.; Alcamo, J. Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. *Glob. Environ. Change* **2013**, *23*, 144–156.
6. Baig, M.B.; Alotibi, Y.; Straquadine, G.S.; Alataway, A. Water resources in the Kingdom of Saudi Arabia: Challenges and strategies for improvement. In *Water Policies in MENA Countries*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 135–160.
7. Aw-Hassan, A.; Rida, F.; Telleria, R.; Bruggeman, A. The impact of food and agricultural policies on groundwater use in Syria. *J. Hydrol.* **2014**, *513*, 204–215.
8. Guermazi, E.; Milano, M.; Reynard, E.; Zairi, M. Impact of climate change and anthropogenic pressure on the groundwater resources in arid environment. *Mitig. Adapt. Strateg. Glob. Change* **2019**, *24*, 73–92.
9. Almazroui, M.; Nazrul Islam, M.; Athar, H.; Jones, P.; Rahman, M.A. Recent climate change in the Arabian Peninsula: Annual rainfall and temperature analysis of Saudi Arabia for 1978–2009. *Int. J. Climatol.* **2012**, *32*, 953–966.
10. MEWA. *Ministry of Environment Water and Agriculture of Saudi Arabia Statistical Report*; Ministry of Environment Water and Agriculture: Riyadh, Saudi Arabia, 2024.
11. GASTAT. *Saudi Arabia Agricultural Statistics*; General Authority for Statistics: Riyadh, Saudi Arabia, 2024**.**
12. Camp, C.; Lamm, F.; Evans, R.; Phene, C. Subsurface drip irrigation–Past, present and future. In Proceedings of the Fourth Decennial National Irrigation Symposium, Phoenix, Arizona, 14–16 November 2000; pp. 14–16.
13. Thompson, T.; Pang, H.-C.; Li, Y.-Y. The Potential Contribution of Subsurface Drip Irrigation to Water-Saving Agriculture in the Western USA. *Agric. Sci. China* **2009**, *8*, 850–854. https://doi.org/10.1016/S1671-2927(08)60287-4.
14. Elawady, M.N.; Abd El-Salam, M.F.; Elnawawy, M.M.; El-Farrah, M.A. Surface and subsurface irrigation effects on Spinach and sorghum. In Proceedings of the 11th Annual Conference of Misr Society of Agricultural Engineers, Kafr El-Sheikh, Egypt, 15–16 October 2003; pp. 118–130.
15. Zhang, F.; Wang, X.; Liu, S.; Ren, H.; Wang, Y.; Han, J. Effects of different pipe burial depths on crop yield, water productivity, and irrigation water productivity: A global meta–analysis. *Eur. J. Agron.* **2025**, *166*, 127562. https://doi.org/10.1016/j.eja.2025.127562.
16. Sivanappan, R.; Rajgopal, A.; Paliniswami, D. Response of vegetable to the drip irrigation. *Madras Agric. J.* **1974**, *65*, 576–579.
17. Yaragattikar, A.; Itnal, C. Soil moisture distribution pattern as influenced by water application rates through drip in deep black soils. *Karnataka J. Agric. Sci.* **2003**, *16*, 121–123.

18. Thorburn, P.J.; Cook, F.J.; Bristow, K.L. Soil-dependent wetting from trickle emitters: Implications for system design and management. *Irrig. Sci.* **2003**, *22*, 121–127.
19. Neshat, A.; Nasiri, S. Finding the optimized distance of emitters in the drip irrigation in loam-sandy soil in the Ghaeme Abad plain of Kerman, Iran. *Middle East J. Sci. Res.* **2012**, *11*, 426–434. Faisalabad.
20. Alomran, A.; Luki, I. Effects of deficit irrigation on yield and water use of grown cucumbers in Saudi Arabia. *WIT Trans. Ecol. Environ.* **2012**, *168*, 353–358.
21. Ismail, S.M. Influence of deficit irrigation on water use efficiency and bird pepper production (*Capsicum annuum* L.). *Meteor. Environ. Arid. Land Agric. Sci.* **2010**, *21*, 21–22.
22. Rahil, M.; Qanadillo, A. Effects of different irrigation regimes on yield and water use efficiency of cucumber crop. *Agric. Water Manag.* **2015**, *148*, 10–15.
23. Patanè, C.; Tringali, S.; Sortino, O. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Sci. Hortic.* **2011**, *129*, 590–596.
24. Fereres, E.; Soriano, M.A. Deficit irrigation for reducing agricultural water use. *J. Exp. Bot.* **2007**, *58*, 147–159. https://doi.org/10.1093/jxb/erl165.
25. Geerts, S.; Raes, D. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Manag.* **2009**, *96*, 1275–1284. https://doi.org/10.1016/j.agwat.2009.04.009.
26. Singh, M.; Singh, P.; Singh, S.; Saini, R.K.; Angadi, S.V. A global meta-analysis of yield and water productivity responses of vegetables to deficit irrigation. *Sci. Rep.* **2021**, *11*, 22095.
27. Mannini, P. Effects of different irrigation scheduling and systems on yield response of melon and cucumber. In Proceedings of the IV International Symposium on Water Supply and Irrigation in the Open and under Protected Cultivation 228, Padova, Italy, 26–28 August 1985; pp. 155–162.
28. Hezarjaribi, A.; Dehghani, A.; Helghi, M.M.; Kiani, A. Hydraulic Performances of Various Trickle Irrigation Emitters. 2008. Available online: https://www.cabidigitallibrary.org/doi/full/10.5555/20093075241 (accessed on 1 July 2026).
29. Grafton, R.Q.; Williams, J.; Perry, C.J.; Molle, F.; Ringler, C.; Steduto, P.; Udall, B.; Wheeler, S.A.; Wang, Y.; Garrick, D. The paradox of irrigation efficiency. *Science* **2018**, *361*, 748–750.
30. Alazba, A.A.; Mattar, M.A.; El-Shafei, A.; Radwan, F.; Ezzeldin, M.; Alrdyan, N. Daily Reference Evapotranspiration Derived from Hourly Timestep Using Different Forms of Penman–Monteith Model in Arid Climates. *Water* **2025**, *17*, 2272. https://doi.org/10.3390/w17152272.
31. American Public Health Association. *Standard Methods for the Examination of Water and Wastewater*; American Public Health Association: Washington, DC, USA, 2005.
32. Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture*; Food and Agriculture Organization of the United Nations Rome: Rome, Italy, 1985; Volume 29.
33. Abedin, T. Improving moisture distribution pattern of subsurface drip irrigation in sandy soil by using synthetic soil conditioner. *Misr J. Ag. Eng* **2006**, *23*, 374–398.
34. Krug, H.; Lorenz, O.A.; Maynard, D.N. *Knott's Handbook for Vegetable Growers*; John Wiley & Sons: New York, NY, USA; Chichester, UK; Brisbane, TO, Canada, 1980.
35. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao Rome* **1998**, *300*, D05109.
36. Bralts, V.F.; Edwards, D.M.; Wu, I.P. Drip irrigation design and evaluation based on the statistical uniformity concept. *Adv. Irrig.* **1987**, *4*, 67–117.
37. *EP405.1*; Design and Installation of Micro Irrigation Systems. ASABE: St. Joseph, MI, USA, 2008.
38. Keller, J.; Karmeli, D. Trickle irrigation design rain bird sprinkler manufacturing crop. *Glendor Calfi* **1975**, *91740*, 24–26.
39. Aiswarya, L.; Siddharam; Sandeepika, M. Soil Moisture Distribution Pattern under Drip Irrigation in Sandy Loam Soil Using Gravimetric Method. *Asian J. Soil Sci. Plant Nutr.* **2024**, *10*, 198–204. https://doi.org/10.9734/ajsspn/2024/v10i2276.
40. Howell, T.A. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* **2001**, *93*, 281–289.
41. Amosson, S.; Almas, L.; Girase, J.R.; Kinney, N.; Guerrero, B. *Economics of Irrigation Systems*; Texas AgriLife Extension Service: College Station, TX, USA, 2011.
42. Lamm, F.R.; Trooien, T.P. Subsurface drip irrigation for corn production: A review of 10 years of research in Kansas. *Irrig. Sci.* **2003**, *22*, 195–200. https://doi.org/10.1007/s00271-003-0085-3.
43. Thebaldi, M.S.; Lima, L.A.; Almeida, W.F.d.; Andrade, R.R. Backpressure effects on the flow-pressure relation of driplines. *Eng. Agric.* **2016**, *36*, 55–62.

44. Goldberg, D.; Gornat, B.; Bar, Y. The Distribution of Roots, Water and Minerals as a Result of Trickle Irrigation. *J. Am. Soc. Hortic. Sci.* **1971**, *96*, 645–648.
45. El Marazky, M.S.A.; Mohammad, F.S.; Al-Ghobari, H.M. Evaluation of soil moisture sensors under intelligent irrigation systems for economical crops in arid regions. *Am. J. Agric. Biol. Sci.* **2011**, *6*, 287–300.
46. Douh, B.; Mguidiche, A.; Bhouri-Khila, S.; Mansour, M.; Harrabi, R.; Boujlben, A. Yield and Water Use Efficiency of cucumber (*Cucumis sativus* L.) conducted under subsurface drip irrigation system in a Mediterranean Climate. *J. Environ. Sci. Toxicol. Food Technol.* **2013**, *2*, 46–51.
47. Al-Harbi, A.R.; Al-Omran, A.M.; Alharbi, K. Grafting improves cucumber water stress tolerance in Saudi Arabia. *Saudi J. Biol. Sci.* **2018**, *25*, 298–304. https://doi.org/10.1016/j.sjbs.2017.10.025.
48. Arbat Pujolràs, G.; Lamm, F.R.; Abou Kheira, A.A. Subsurface drip irrigation emitter spacing effects on soil water redistribution, corn yield and water productivity. *Appl. Eng. Agric.* **2010**, *26*, 391–399.
49. Zin El-Abedin, T.K.; Mattar, M.A.; Alazba, A.A.; Al-Ghobari, H.M. Comparative effects of two water-saving irrigation techniques on soil water status, yield, and water use efficiency in potato. *Sci. Hortic.* **2017**, *225*, 525–532. https://doi.org/10.1016/j.scienta.2017.07.044.
50. Assouline, S. The effects of microdrip and conventional drip irrigation on water distribution and uptake. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1630–1636.
51. Evans, R.O.; Cassel, D.; Sneed, R. Soil, Water, and Crop Characteristics Important to Irrigation Scheduling. 1991. Available online: https://content.ces.ncsu.edu/soil-water-and-crop-characteristics-important-to-irrigation-scheduling (accessed on 1 July 2026).
52. Ayas, S.; Demirtas, C. Deficit irrigation effects on cucumber (*Cucumis sativus* L. *Maraton*) yield in unheated greenhouse condition. *J. Food Agric. Environ.* **2009**, *7*, 645–649.
53. Tüzel, I.; Tüzel, Y.; Öztekin, G.; Meric, M.; Whalley, R.; Lock, G. Response of cucumber to deficit irrigation. In Proceedings of the International Symposium on Strategies Towards Sustainability of Protected Cultivation in Mild Winter Climate 807, Antalya, Turkey, 7–10 April 2008; pp. 259–264.
54. Yuan, B.-Z.; Sun, J.; Kang, Y.; Nishiyama, S. Response of cucumber to drip irrigation water under a rainshelter. *Agric. Water Manag.* **2006**, *81*, 145–158.
55. Wang, Z.; Liu, Z.; Zhang, Z.; Liu, X. Subsurface drip irrigation scheduling for cucumber (*Cucumis sativus* L.) grown in solar greenhouse based on 20 cm standard pan evaporation in Northeast China. *Sci. Hortic.* **2009**, *123*, 51–57.
56. Hanson, B.; Schwankl, L.; Schulbach, K.; Pettygrove, G. A comparison of furrow, surface drip, and subsurface drip irrigation on lettuce yield and applied water. *Agric. Water Manag.* **1997**, *33*, 139–157.
57. Al-Ghobari, H. A comparison of water application uniformity for drip irrigation system above and below soil surface at various soil depths and scheduling techniques in arid region. *WIT Trans. Ecol. Environ.* **2012**, *168*, 311–322.
58. Aly, A.; Al-Omran, A.; Khasha, A. Water management for cucumber: Greenhouse experiment in Saudi Arabia and modeling study using SALTMED model. *J. Soil Water Conserv.* **2015**, *70*, 1–11.
59. Al-Omran, A.; Louki, I.; Aly, A. A comparative study of the impact of deficit irrigation on cucumber yields planted in a greenhouse and an open field in an arid environment. *WIT Trans. Ecol. Environ.* **2014**, *185*, 113–124.
60. Zhang, H.-x.; Qun, W.; Jun, F. Yield and quality response of cucumber to irrigation and nitrogen fertilization under subsurface drip irrigation in solar greenhouse. *Agric. Sci. China* **2011**, *10*, 921–930.
61. Hayat, S.; Hayat, Q.; Alyemeni, M.N.; Wani, A.S.; Pichtel, J.; Ahmad, A. Role of proline under changing environments: A review. *Plant Signal. Behav.* **2012**, *7*, 1456–1466. https://doi.org/10.4161/psb.21949.
62. Szabados, L.; Savouré, A. Proline: A multifunctional amino acid. *Trends Plant Sci.* **2010**, *15*, 89–97. https://doi.org/10.1016/j.tplants.2009.11.009.
63. Sahin, U.; Kuslu, Y.; Kiziloglu, F. Response of cucumbers to different irrigation regimes applied through drip-irrigation system. *J. Anim. Plant Sci* **2015**, *25*, 198–205.
64. Ertek, A.; Şensoy, S.; Gedik, İ.; Küçükyumuk, C. Irrigation scheduling based on pan evaporation values for cucumber (*Cucumis sativus* L.) grown under field conditions. *Agric. Water Manag.* **2006**, *81*, 159–172. https://doi.org/10.1016/j.agwat.2005.03.008.
65. Fanourakis, D.; Makraki, T.; Spyrou, G.P.; Karavidas, I.; Tsaniklidis, G.; Ntatsi, G. Environmental Drivers of Fruit Quality and Shelf Life in Greenhouse Vegetables: Species-Specific Insights. *Agronomy* **2026**, *16*, 48. https://doi.org/10.3390/agronomy16010048.
66. Parkash, V.; Singh, S.; Deb, S.K.; Ritchie, G.L.; Wallace, R.W. Effect of deficit irrigation on physiology, plant growth, and fruit yield of cucumber cultivars. *Plant Stress* **2021**, *1*, 100004. https://doi.org/10.1016/j.stress.2021.100004.

67. Pérez-Blanco, C.D.; Hrast-Essenfelder, A.; Perry, C. Irrigation Technology and Water Conservation: A Review of the Theory and Evidence. *Rev. Environ. Econ. Policy* **2020**, *14*, 216–239. https://doi.org/10.1093/reep/reaa004.
68. Fanourakis, D.; Tsaniklidis, G.; Makraki, T.; Nikoloudakis, N.; Bartzanas, T.; Sabatino, L.; Fatnassi, H.; Ntatsi, G. Climate Change Impacts on Greenhouse Horticulture in the Mediterranean Basin: Challenges and Adaptation Strategies. *Plants* **2025**, *14*, 3390. https://doi.org/10.3390/plants14213390.
69. Davies, P.A.; Paton, C. The Seawater Greenhouse: Background, theory and current status. *Int. J. Low-Carbon Technol.* **2006**, *1*, 183–190. https://doi.org/10.1093/ijlct/1.2.183.
70. Mastouri, H.; Morchid, H.; Derraz, M.; Remaidi, M.; Ennawaoui, C. Atmospheric water harvesting for climate-resilient water–energy systems: A review of technologies, design, operation and performance metrics. *Results Eng.* **2026**, *30*, 110278. https://doi.org/10.1016/j.rineng.2026.110278.
71. De Gelder, A.; Dieleman, J.A.; Bot, G.P.A.; Marcelis, L.F.M. An overview of climate and crop yield in closed greenhouses. *J. Hortic. Sci. Biotechnol.* **2012**, *87*, 193–202. https://doi.org/10.1080/14620316.2012.11512852.
72. Opdam, J.J.G.; Schoonderbeek, G.G.; Heller, E.M.B.; de Gelder, A. *Closed Greenhouse: A Starting Point for Sustainable Entrepreneurship in Horticulture*; International Society for Horticultural Science (ISHS): Leuven, Belgium, 2005; pp. 517–524.
73. Al-Othman, A.A.; El-Shinawy, D.M.; Oraiath, A.A.T.; Elwakeel, A.E.; Dewidar, A.Z.; Elbeltagi, A.; Hamza, A. Effects of a Magnetic Field on Surface and Subsurface Drip Irrigation Water, Tomato Plants and Desert Sandy Soil Characteristics. *Irrig. Drain.* **2026**, *75*, 600–619.
74. Fatima, Z.; Benaafi, M.; Tawabini, B.; Hanafy, S.; Basaleh, A. Experimental-based assessment of managed aquifer recharge with treated wastewater in arid coastal regions. *Phys. Chem. Earth Parts A/B/C* **2026**, *144*, 104602. https://doi.org/10.1016/j.pce.2026.104602.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.