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Precision Agriculture Approaches for Enhancing Cut Roses Yield and Irrigation Water Sustainability Under Soilless Systems

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ABSTRACT: Introduction: Optimizing irrigation use efficiency in soilless culture systems is a critical challenge, particularly for high-value ornamental crops like cut roses facing escalating irrigation scarcity.

Objective: This study aimed to quantitatively evaluate the actual evapotranspiration ( ), agronomic traits, and irrigation savings of cut roses under automated, sensor-driven precision irrigation.

Methods: A field experiment was carried out in a smart greenhouse in the 2023-2024 season in a biphasic planter box (peat-perlite 1:2 v/v). A GS3 dielectric sensor-controlled automated fertigation system was employed to provide four treatments of drip irrigation: full crop requirement, 75%, 50%, and 25%. (F1: 1500 mm, 100%) as a control, and three regulated deficit thresholds (F2: 1125 mm [75%]; F3: 750 mm [50%]; and F4: 500 mm [33.3%]).

Results: The sensor-based architecture accurately tracked spatiotemporal moisture dynamics, enabling substantial irrigation savings of 25%, 50%, and 66.6% for F2, F3, and F4, respectively. Agronomically, the non-limiting F1 regime maximized floral yield, showing significant increases of 9%, 19%, and 32% compared to the F2, F3, and F4 treatments. Concurrently, severe moisture depletion (F4) significantly suppressed structural growth and leaf area index. Conclusion: Integrating real-time sensor telemetry with localized surface drip systems provides a sustainable framework for managing finite irrigation resources, dynamically balancing cut rose productivity with high irrigation conservation efficacy in advanced agricultural environments.

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1. INTRODUCTION

With the continuing escalation of the global water crisis and the multifaceted effects of climate change, a paradigm shift in water management in agriculture is needed particularly for high value crops such as cut roses (*Rosa damascena* Mill). The traditional watering and fertilization practice is frequently associated with inefficient use of water and leaching of nutrients. This has led the switch to soilless culture systems, which involve the use of biphasic substrates like peat moss and perlite, to become a key measure for improving water use efficiency (WUE) and environmental sustainability (Gruda, 2019; Balliu *et al.*, 2021). The distinctive hydraulic characteristics of these very porous media, however, creates significant management problems: these media drain very rapidly, and the acute changes in moisture in the active root zone are very sensitive to plants.

Therefore, the incorporation of precision agriculture and IoT (Internet of Things) technologies is essential to tackle these risks (García *et al.*, 2020). Smart fertigation systems based on advanced dielectric sensors such as high-frequency capacitance probes allow the acquisition of important edaphic parameters in real-time, such as the Volumetric Water Content (VWC), the Electrical Conductivity (EC) and the Substrate Temperature (Montesano *et al.*, 2018). Unlike traditional time-based irrigation scheduling, sensor-based systems act as a moving tool for decision making, that activates irrigation events when the moisture level hits physiological thresholds. This is a continuous spatiotemporal telemetry to avoid both root asphyxiation under saturated conditions and severe drought stress during depletion stages (Aoda *et al.*, 2021).

Regulated deficit irrigation is a proven technique for water saving in native soils and is more complex in limited soilless media. The root system of the rose is very sensitive to moisture gradients, and cutting off water at any arbitrary time can seriously affect the stomatal conductance, photosynthetic efficiency and the final yield of the flower (Balliu *et al.*, 2021). Therefore, the exact physiological limits to deficit irrigation in peat-perlite substrates is very important in achieving maximum water saving without compromising sustainable commercial productivity.

Based on this, the present study was designed to establish a high efficiency precision irrigation system for cut roses in soilless culture in the smart greenhouse environment. The particular objectives were to: (1) continuously monitor root-zone moisture dynamics using an automated, AI-integrated dielectric sensor array; (2) quantify the actual evapotranspiration (ET_c) and water savings under full irrigation (100% ET_c) and three progressive deficit thresholds (75%, 50%, and 33.3% ETc); and (3) critically evaluate the impact of these automated deficit regimes on key agronomic traits, specifically leaf area development and total floral yield.

2. MATERIALS AND METHODS

2.1. Experimental Site and Soilless System Setup

A field experiment was conducted during the 2023-2024 growing season inside a smart greenhouse (504 m²; 9 m × 56 m) located in the Al-Amiriya district, Baghdad, Iraq (33°17'10.6" N, 44°16'24.1" E, 33 m a.s.l.). The cultivation was performed using a soilless system (planter boxes/bag culture) raised 0.95 m above ground level. Each planter box (1.75 m length × 0.5 m width × 0.4 m depth) was filled with a biphasic mixture of pH-adjusted black peat moss and agricultural perlite in a 1:2 volume-to-volume ratio. The physicochemical properties of the media constituents are detailed in Table 1.

Table 1. Presents the technical specifications of Perlite and Black Peat Moss (ASAE, 2003)

Measured property	Perlite	Black peat muse
Air capacity	20-25 vol%	25-30 vol%
Water capacity	59-68.9 vol%	60-65 vol%
Total pore volume	68 vol%	91 vol%
Dry matter	0	9 vol%
PH	7-7.5	6.5-7
Fraction	25-30 mm coarse	10-25 mm medium

Four commercial cultivars of cut roses (*Rosa damascena* Mill.) with red, yellow, white and pink phenotypic variations from certified Dutch plants were planted. Ten seedlings were placed in each planter box in a localized geometry of 0.30 m and 0.30 m intra-row and inter-row spacing, respectively. All planters were fitted with an efficient subsurface drainage system which diverted excess leachates from the basal region of each to a central storage pond, to prevent water logging.

2.2. Experimental Design and irrigation Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with four replications. The study evaluated four automated surface drip irrigation treatments based on the total seasonal crop moisture requirement (ETc), which was estimated at 1500 mm season^{-1} following standard FAO guidelines:

- **F1 (Control):** Full irrigation representing 100% of the crop moisture requirement (1500 mm).
- **F2:** Mild deficit irrigation at 75% of the requirement (1125 mm).
- **F3:** Moderate deficit irrigation at 50% of the requirement (750 mm).
- **F4:** Severe deficit irrigation at 33.3% of the requirement (500 mm).

The greenhouse consisted of several lines of cultivation with a spatial buffer of 0.75 m between blocks. A treatment was assigned to an experimental unit of seven planters which were contiguous, giving 112 planters (4 treatments × 7 planters × 4 replications) and an effective localized density of 70 plants per treatment.

2.3. Automated Fertigation and Sensor Telemetry

irrigation and fertigation were dynamically managed using a smart central control unit (Commander EVO PLUS, Irritec, Italy). The system was equipped with a surface drip network (GR type) utilizing pressure-compensating (PC) emitters with a discharge rate of 1.35 L h^{-1}.

A distributed system of dielectric sensor (GS3, METER Group/Irritec) located in the active root zone (0.30 m depth) throughout the experimental units, enabled real-time decision support. These sensors were capable of regularly and frequently measuring Volumetric Moisture Content (VWC, accuracy within 15 %), Electric Conductivity (EC, accuracy within 10 %) and soilless temperature (accuracy within 1.0 °C). These inputs were fed into a central controller, which automatically controls irrigation events and proportionately feeds nutrients while keeping the pH and EC levels in check. Fidelity in reading was maximized by using media-specific calibrations for the highly porous peat-perlite mixture. For organic substrates maintaining an EC below 4 dS m^{-1}, the VWC was derived from the apparent dielectric permittivity (ϵ_a) using the specific polynomial equation (Decagon Devices, 2016):

$$\text{VWC} = 0.118\ \epsilon_a - 0.117 \ldots\ldots\ldots ①$$

A comprehensive photographic documentation of the experimental setup, including the soilless mixture, fertigation control devices, and visual phenotypic comparisons of the plants under varying irrigation treatments, is provided in Appendix A (Figure A1).

2.4. Irrigation Scheduling and Moisture Assessment

The irrigation events were only activated when the moisture in the soilless reached the desired moisture levels (75%, 50%, and 33.3% of the readily available moisture in the soilless environment compared to the F1 control). The depth of irrigation (d) required per irrigation to bring the soilless back to field capacity was determined from the known moisture retention curve for the peat-perlite mixture by the following equation: (Cuenca, 1989):

$$d = (\theta_{fc} - \theta_i) \times D \ldots\ldots\ldots ②$$

Where d is the applied irrigation depth (mm), θ_{fc} is the volumetric moisture content at field capacity (cm^3 cm^{-3}), θ_i is the volumetric moisture content immediately prior to irrigation (cm^3 cm^{-3}), and D is the effective root zone depth (m).

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To accurately adjust the applied moisture volume via the localized surface drip system, a reduction coefficient (K_r) was incorporated, reflecting the actual canopy coverage (Keller and Bliesner, 2001):

$$K_r = \left(\frac{Ac}{L \times W}\right)^{0.85} \quad \ldots\ldots\ldots ③$$

Where Ac is the shaded canopy area (m²), L is the intra-row spacing (m), and W is the inter-row spacing (m).

2.5. Determination of Applied irrigation and Actual water Consumption

The total depth of applied irrigation (I) for each treatment was accurately quantified using the emitter discharge rate and the duration of each operational event. Furthermore, the actual evapotranspiration (ET_a) was calculated using a modified water balance equation (Pereira *et al.*, 2025). Since the greenhouse is a controlled environment, and the soilless culture system is closed, there is no precipitation, surface runoff and deep percolation. Therefore, the ET_a was derived directly from the applied irrigation depth and the fluctuations in substrate moisture content, which were continuously monitored by the dielectric sensors.

The applied irrigation depth was calculated as follows:

$$I = \frac{q \times t \times n}{A} \quad \ldots\ldots\ldots ④$$

Where I is the total applied irrigation depth (mm), q represents the emitter discharge rate (L h^{-1}), t is the duration of the irrigation event (h), n denotes the number of emitters per plant, and A is the allocated surface area per plant (m²).

The actual crop evapotranspiration was determined using the simplified water balance equation:

$$ET_a = I \pm \Delta S \quad \ldots\ldots\ldots ⑤$$

Where ET_a is the actual crop evapotranspiration (mm), I represents the total applied irrigation depth (mm), and ΔS indicates the change in volumetric moisture content in the root zone (mm), calculated from the sensors readings before and after irrigation events.

2.6. Evaluation of Sustainability and water Use Efficiency

Water use efficiency indexes were developed according to the suggestion of (Pereira *et al.*, 2012), to quantitative the agricultural and environmental sustainability of the tested regimes. These parameters are considered as the ultimate parameters for the management of sustainable resources which directly assess the commercial yield of flowers and the conservation of the resources (subsequently illustrated in Figure 5). The water use efficiency in field (FWUE) was determined as the ratio of total floral yield (flowers plant-1) to the total volume of applied irrigation water (m³). On the other hand, the crop water use efficiency (CWUE) was computed as the ratio of floral yield to actual evapotranspiration (*ETa* in m³) that was accurately measured by the dielectric sensors in the soilless media. These indicators were used to determine the optimum combination for sustainable production of the greenhouse.

$$FWUE = \frac{\text{Floral Yield (flowers plant}^{-1})}{\text{Applied Irrigation Water (m}^3)} \quad \ldots\ldots\ldots ⑥$$

$$CWUE = \frac{\text{Floral Yield (flowers plant}^{-1})}{\text{Actual Evapotranspiration (m}^3)} \quad \ldots\ldots\ldots ⑦$$

2.7. Agronomic Parameters and Statistical Analysis

Throughout the 210-day cultivation period, structural and yield parameters were systematically recorded, including plant height (m), leaf area (m²), leaf area index (LAI), and the cumulative weekly yield of harvested flowers per plant. The acquired data were subjected to Analysis of Variance (ANOVA) suitable for the RCBD design. Mean comparisons among the

irrigation treatments were performed using the Least Significant Difference (LSD) test at a 95% confidence level ($p \leq 0.05$).

3. RESULTS AND DISCUSSION

3.1. Actual Evapotranspiration and Sensor-Driven Dynamics

The actual evapotranspiration (*ETa*) patterns over the phenological stages are shown in Table 2 and in Figures 1-4. Water use was highest during the vegetative growth stage for all irrigation treatments, and was about 35% of the total seasonal water use. This is a physiologic expression of the high transpiration rate associated with the high growth rate of the canopy and the maximum leaf area development (Katsoulas *et al.*, 2006). Water demand was also high (around 33%) at the flower bud initiation phase, indicating the high metabolic energy needed for the initiation of floral differentiation and organogenesis (Raviv *et al.*, 2019).

The continuous sensor profiles corroborate these trends, demonstrating clear differences in moisture content of the soil volume with respect to depth of irrigation. The water use was, indeed, decreased in both the flowering and cropping stages of the crop (by 19% and 12% respectively as expected). This reduction is a function of canopy maturity and the end of terminal growth and a relative reduction in the evaporative demand of the atmosphere .

Intriguingly, the total volumes of water used in F1, F2, F3 and F4 treatments (1500, 1125, 750, and 504 mm) varied significantly, but the percentage of water used per stage was very similar (Table 2). This indicates that, except for the basic phenological sequence, the deficit irrigation treatments were successful in reducing plant growth rates. In the critical moisture stress (F4) it is equivalent of metabolic scaling. Due to the limited water supply, stomatal closure occurs, which greatly reduces carbon assimilation and the uptake of root nutrients (Balliu *et al.*, 2021). Thus, although proportional timing is retained, absolute output of structure and flowers is catastrophically reduced (Aoda *et al.*, 2021).

Table 2. Actual water consumption (ET_a) across phenological growth stages of cut roses under varying surface drip irrigation regimes (100%, 75%, 50%, and 33.3% ET_c) during the 2023–2024 season.

		F1				F2				
Phenological Stage	**Vegetative Growth**	**Bud initiation**	**Flowering**	**Harvest**	**Total**	**Vegetative Growth**	**Bud initiation**	**Flowering**	**Harvest**	**Total**
Duration (days)	75	70	40	25	210	75	70	40	25	210
Stage ET_a (mm)	535.725	500.01	285.72	178.575	1500	402	375	214	134	1125
Relative ET_a (%)	35.715	33.334	19.048	11.903	100	35.733	33.35	19.02	11.9	100.003
Daily rate (mm day^{-1})	7.143	7.143	7.143	7.143	-	5.36	5.35	5.35	5.36	-
Number of Irrigations	22	20	18	10	70	18	18	14	9	59
Mean applied depth ((mm)	24.35	25.00	15.873	17.85	-	22.33	20.83	15.28	14.88	-
		F3				**F4**				
Phenological Stage	**Vegetative Growth**	**Bud initiation**	**Flowering**	**Harvest**	**Total**	**Vegetative Growth**	**Bud initiation**	**Flowering**	**Harvest**	**Total**
Duration (days)	75	70	40	25	210	75	70	40	25	210
Stage ET_a (mm)	267.75	249.9	142.8	89.25	749.7	180	168	96	60	504
Relative ET_a (%)	35.7	33.32	19.04	11.9	99.96	36	33.6	19.2	12	100.8
Daily rate (mm day^{-1})	3.57	3.57	3.57	3.57	-	2.4	2.4	2.4	2.4	-

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Number of Irrigations	13	12	12	8	45	10	10	7	5	32
Mean applied depth ((mm)	20.59	20.82	11.9	11.15	-	18	16.8	13.71	12	-

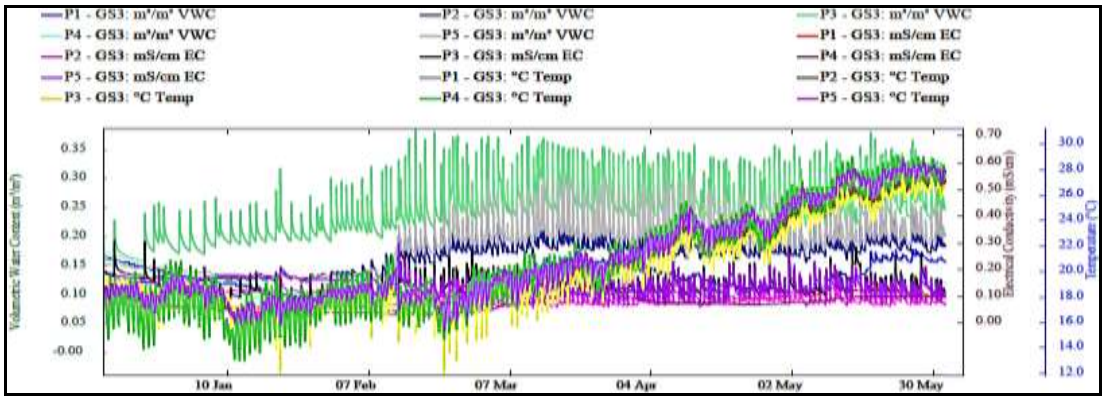


Figure 1. Volumetric water content, salinity, and temperature profiles measured by the five sensors under the full irrigation treatment (100% ET_c).

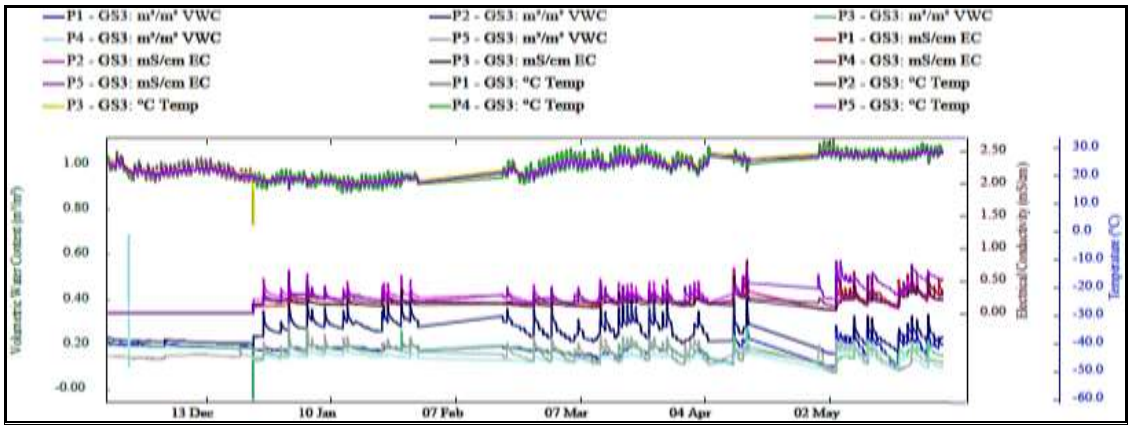


Figure 2. Volumetric water content, salinity, and temperature profiles measured by the five sensors under the 75% deficit irrigation treatment (75% ET_c).

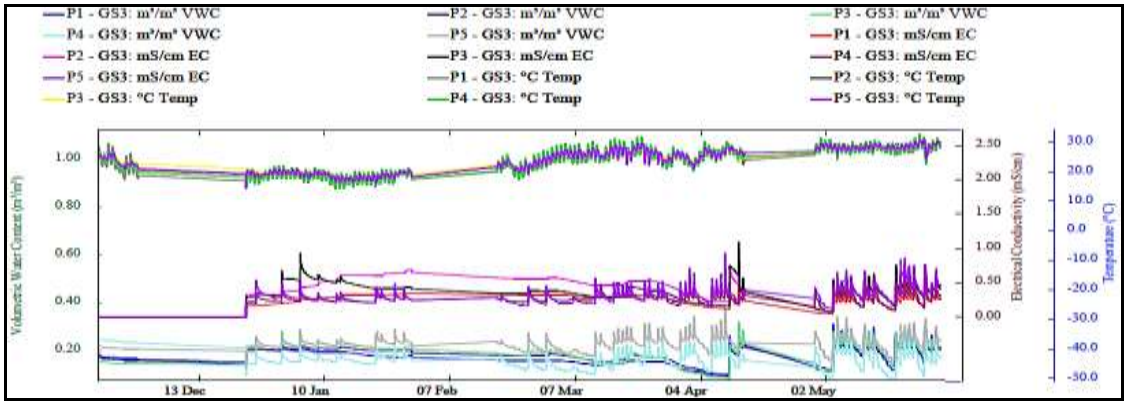


Figure 3. Volumetric water content, salinity, and temperature profiles measured by the five sensors under the 50% deficit irrigation treatment (50% ET_c).

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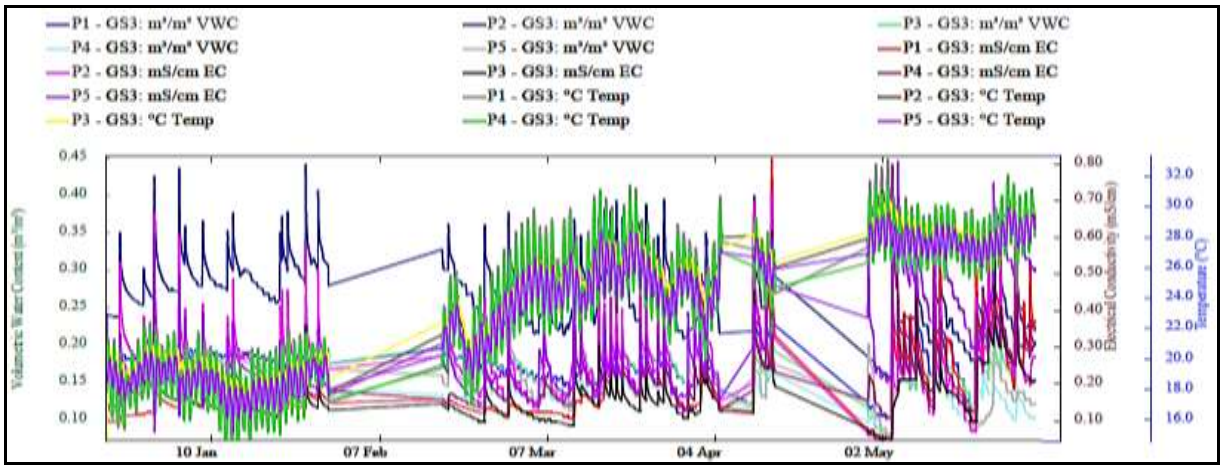


Figure 4. Volumetric water content, salinity, and temperature profiles measured by the five sensors under the 33.3% deficit irrigation treatment (33.3% ET_c).

3.2. Effect of Irrigation Treatments on Plant Traits

Table 3 demonstrates the profound impact of the irrigation treatments on key agronomic traits. The full irrigation regime (100% ET_c) significantly maximized plant height, total leaf area, leaf area index (LAI), number of leaves, and total floral yield. Conversely, as the water deficit intensified, all growth metrics declined proportionally. The severe deficit treatment (33.3% ET_c) induced critical reductions across all measured parameters compared to the control. Physiologically, this decrease, under moisture stress, is explained by a decrease in the turgidity pressure of the cells which in turn decreases the cellular growth, the development of leaves and the stomatal conductance. As a result, the limited photosynthetic ability significantly reduces the amount of assimilates that can be allocated to structural growth and floral initiation (Abafita *et al.*, 2014). Moreover, severe moisture stress during critical flowering stage seriously affects the efficiency of pollination and emergence of flowers (Farooq *et al.*, 2009). The 75% treatment had moderate reductions in yield and vegetative growth; however it had an acceptable commercial performance when compared with the more severe treatment deficit 50% and 33.3% deficit irrigation.

Table 3. Effect of varying surface drip irrigation regimes on the vegetative and floral traits of cut roses during the 2023-2024 season.

Cut roses (after 210 days from planting)					
Treatment **Plant growth traits**	**%100**	**%75**	**%50**	**%30**	**L.S.D.**
Plant height (m)	0.78	0.71	0.64	0.55	**0.120**
Number of leaves per plant	23.5	20.6	18.7	16.5	**2.038**
Number of flowers per plant	118.0	107.0	95.7	80.5	**9.954**
Total leaf area (m^2)	1.75	1.29	1.15	1.00	**0.098**
Leaf area index	7.987	5.986	5.337	4.922	**0.489**

3.3. Field and Crop water Use Efficiency (FWUE and CWUE)

Figure 5 illustrates the dual-axis relationship between floral yield and both field water use efficiency (FWUE) and crop water use efficiency (CWUE). The graphical representation indicates a significant inverse relationship between the applied irrigation volume and water efficiency. Although the full irrigation treatment (F1, 100%) produced the maximum absolute floral yield (118.0 flowers $plant^{-1}$), it recorded the lowest FWUE and CWUE (874.1 flowers m^{-3}).

In contrast, the efficiency values rose significantly as water shortage worsened. The highest efficiency was obtained for severe 33.3% deficit irrigation treatment (F4) with 1788.9 flowers m^{-3} for FWUE and 1774.7 flowers m^{-3} for CWUE, respectively. The physiological reason is that when plants are moderately and mildly moisture-stressed, they tend to partially close their stomata. This regulatory mechanism has a faster effect on transpiration losses than on carbon assimilation (Chaves *et al.*, 2009). In this way, the root system optimizes the use of all the water that is available for the production of biomass and flowers, which has been well documented in deficit irrigation (Fereres and Soriano, 2007).

However, selecting the optimal irrigation regime requires balancing high efficiency with commercial profitability. While the F4 treatment maximizes efficiency, the severe yield penalty (dropping to 80.5 flowers $plant^{-1}$) makes it commercially unviable. Thus, deficit irrigation of 75% (F2) is found as the optimum irrigation level. F2 (1056.8 flowers m^3) has a greatly improved FWUE with an excellent floral yield (as shown in Fig. 5). (107.0 flowers $plant^{-1}$) in the soilless culture system, aligning with sustainable agricultural practices (Geerts and Raes, 2009).

The near-identical values between FWUE and CWUE arise from the highly controlled nature of the soilless culture system. Under precision surface drip irrigation, deep percolation and surface runoff are virtually eliminated. Consequently, the total applied water volume closely matches the actual evapotranspiration (ET_a) recorded by the sensors. This high application efficiency ensures that nearly all applied water is effectively utilized by the root zone, making field and crop efficiencies statistically comparable.

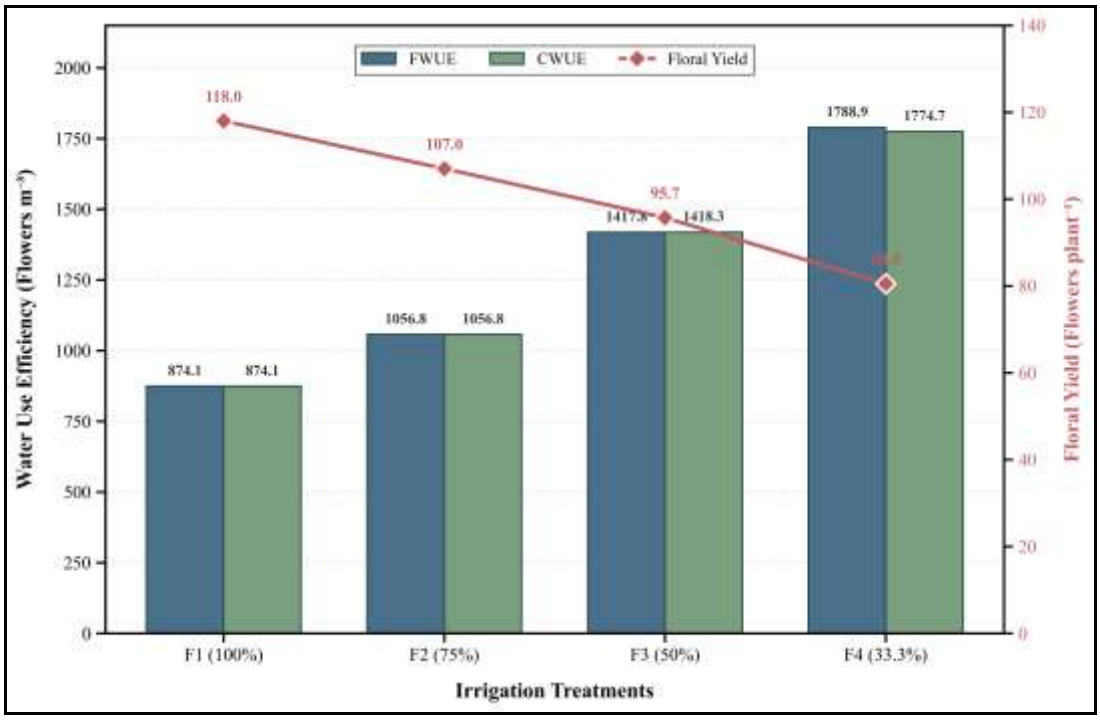


Figure 5. Dual-axis representation of field and crop water use efficiency (FWUE and CWUE) alongside floral yield across varying deficit irrigation regimes (100%, 75%, 50%, and 33.3% ET_c).

3.4. Limitations of the Study

The precision irrigation scheme proved to be highly successful, but there were some limitations. The present results have been achieved in the first growing season under controlled greenhouse conditions under specific arid climate of Iraq. In addition, the accuracy of the dielectric sensors, such as those made by the METER Group (the type used here, the GS3 probes), is extremely dependent upon close sensor specific calibration for each media. These water savings should be used with caution when predicting for other soilless mixes or for completely different environmental conditions.

4. CONCLUSIONS

Real-time workable dielectrics sensors telemetry integrated with localized surface irrigation offers an innovative, sustainable solution for water management of finite resources in high-value ornamental production. The automated system was effective in monitoring the spatiotemporal variation of moisture in the highly porous peat-perlite soilless culture and avoided hypoxia and sudden water loss. The Water Use Efficiency (WUE) was highest under the non-limiting control regime (100% ET_c) and lowest under the limiting control regime (25% ET_c). Conversely, severe moisture depletion (33.3% ET_c) drastically suppressed plant metabolism and structural development, rendering it commercially unviable despite its high FWUE. Therefore, in this study, there is a recommendation to use the 75% deficit irrigation as an optimum agronomic strategy. This regime has the perfect balance as it allows for significant water savings (25%) with water management parameters being used to maximize efficiency, while withholding large penalties on commercial floral quality and yield. Future investigations should aim to assess these automatic deficit algorithms in different soilless mixes for better hydraulic retention to accommodate future perspectives. Additionally, the approach that drives water use decisions using precision sensors could be adapted to other economically important or late-summer crops, like eggplant and maize, and be broadly adopted as a means of addressing global agricultural water shortages.

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Appendix A



Figure A1. Photographic documentation of the experimental setup, detailing the soilless culture components, the automated irrigation and fertigation control units, and the phenotypic development of cut roses under varying irrigation regimes (100%, 75%, 50%, and 33.3% ET_c).