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From clay to crops: improving water productivity in rosemary and lavender under sandy soil conditions in South Africa

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Background: Increasing irrigation water productivity is a key strategy for achieving sustainable agricultural production. This study evaluated the performance of self-regulating low-energy clay-based irrigation (SLECI) as a sustainable alternative to surface and subsurface drip irrigation under water-scarce sandy field conditions, with a particular focus on quantifying the trade-off between irrigation water productivity and fresh biomass yield. SLECI system is a subsurface irrigation technology that uses microporous clay emitters buried within the crop root zone. Water is released passively in response to soil moisture deficits, as water flows through the clay pores only when soil suction exceeds the retention force of the emitter. This self-regulating mechanism delivers water directly to plant roots without the need for pumps, sensors, or external control systems.

Methods: The experiment was conducted on newly established, 1-year plantings of rosemary (*Salvia rosmarinus*, Tuscan Blue variety) and lavender (*Lavandula stoechas*, Hollandia variety) grown under open-field conditions at the Welgevallen Experimental Farm, Stellenbosch, South Africa (33°56'33" S, 18°51'52" E), from November 2023 to February 2024, during the hot-dry summer season.

Results: The highest fresh marketable yield of rosemary was obtained under subsurface drip irrigation (906 kg/ha), while lavender achieved its highest yield under conventional surface drip irrigation (3,625 kg/ha). Although yields under SLECI were lower, this system used substantially less irrigation water (533.2 m³/ha) over the 3-month period, compared with surface drip (6,800 m³/ha) and subsurface drip irrigation (3,060 m³/ha). Irrigation water productivity (IWP) demonstrated the water-saving efficiency of SLECI, producing 0.529 kg of fresh marketable rosemary per m³ of applied water, nearly 4.5 times higher than surface drip irrigation. Similarly, SLECI achieved an IWP of 1.467 kg/m³ for

lavender, representing a more than 2.7-fold increase compared to surface drip irrigation (0.115 kg/m^3). Irrigation technique significantly affected fresh marketable yield. Subsurface drip irrigation and SLECI increased rosemary plant diameter relative to surface drip, whereas subsurface and surface drip irrigation promoted larger lavender plant diameters.

Conclusion: This study contributes to understanding how clay-based irrigation systems perform under severe sandy soil conditions and provides practical insights into the trade-off between water saving and crop productivity in semi-arid environments.

KEYWORDS

deficit irrigation, drip irrigation, sandy soils, SLECI, water efficiency

1 Introduction

Water security is a hot topic all over the world, due to global warming, climate change, natural calamities such as droughts and floods, overuse of water, and other factors (Mohtar and Fares, 2022). Many arid and semi-arid regions in the world are recognized as global hotspots for climate change, facing projections of increased temperatures, reduced rainfall, and more frequent and severe droughts (IPCC, 2021). These changes place immense pressure on freshwater resources, with the agricultural sector, the largest consumer of water, being particularly vulnerable. In such water-scarce environments, the sustainability of agriculture hinges on the adoption of irrigation technologies that maximize water productivity—achieving “more crop per drop” (Soria-Lopez et al., 2023).

High-value aromatic crops like rosemary and lavender are well-suited to their native Mediterranean climates (semi-arid conditions) due to inherent drought tolerance. However, while they can survive dry spells, their commercial yield and quality are significantly enhanced by supplemental irrigation (Singh, 2004; Sałata, 2020; Sałata et al., 2020; La Bella et al., 2021; Ghamarnia et al., 2022; Cáceres-Cevallos et al., 2023). Climate change can have a significant impact on lavender plantations and their irrigation practices, resulting in increased water stress and potential challenges for lavender cultivation (Akçay et al., 2023). Therefore, in the changing climate, plants that previously survived under rainfed conditions are now dependent on irrigation.

Irrigation optimization is critical for sustainable agriculture in water-scarce regions, particularly for drought-tolerant crops like lavender (*Lavandula angustifolia* Mill.), where strategic water management can enhance productivity (Saunier et al., 2022; Hosseini and Heidari, 2025). A study by Yetik and Sen (2025) found that while rainfed lavender yields were significantly reduced, moderate deficit irrigation (33% water deficit) could achieve yields comparable to full irrigation, highlighting the crop's suitability for water-saving strategies (Hassan et al., 2013). In addition, deficit irrigation can improve water use efficiency despite reduced growth, as demonstrated in *Salvia splendens* and *Antirrhinum majus* (Sezen et al., 2023; 2024). Similarly, in lavender, moderate deficit irrigation maintains acceptable yields while significantly increasing water productivity (Akçay et al., 2023).

Ghamarnia et al. (2022) reported that increasing water deficit significantly reduced rosemary growth parameters and essential

oil content, making 50% irrigation unsuitable. For dry matter production, 75% deficit irrigation is acceptable, but full irrigation is necessary for maximum essential oil yield. Furthermore, many other studies have evaluated the positive effect of irrigation on yield and quality characteristics in different herbs and aromatic plants (Pejić et al., 2017; Ekren et al., 2012; Azizi et al., 2009; Baher et al., 2002).

Irrigation is fundamental to global agriculture, accounting for about 70% of freshwater withdrawals worldwide. The water scarcity influenced by climate change and increasing food demand highlights the need for sustainable irrigation (FAO, 2023). Therefore, innovations for saving water in irrigated agriculture and thereby improving water use efficiency are of paramount importance in water-scarce regions (Yazar et al., 2009), often necessitating a shift in focus from maximizing absolute yield to maximizing the efficiency of water use (Yetik and Sen, 2025). Zhang et al. (2025) reported that improved irrigation management can enhance water productivity, even when yield responses are variable.

Modern micro-irrigation systems, such as surface and sub-surface drip, have become standard for improving water efficiency (Lakhier et al., 2024; Çetin and Kara, 2019; Tanaskovik et al., 2016; Mancosu et al., 2015; Tekinel and Kanber, 2002; Papadopoulos, 1996). Sub-surface drip irrigation (SDI) offers a distinct advantage by delivering water directly to the root zone, thereby eliminating non-productive losses from surface evaporation (Mahler, 2024; Guo et al., 2023; Ayars et al., 1999). Other approaches that optimize water use efficiency while reducing energy demand and environmental impacts are innovative clay-based technologies inspired by ancient pitcher irrigation techniques. Among these is the Self-regulating, Low-Energy, Clay-based Irrigation (SLECI) system (Mahler, 2024). SLECI utilizes microporous clay emitters buried underground that release water based on the principle of soil matric potential. Water seeps out only when the surrounding soil becomes dry enough to exert a suction force greater than the water retention capacity of the clay pores, creating a self-regulating, demand-driven system that operates at very low pressure and without external energy or controllers (Malchev et al., 2025, 2022; University of Ss. Cyril Methodius in Skopje, 2025). By delivering water gradually through clay emitters buried below the soil surface, SLECI reduces water loss from evaporation and deep percolation compared to surface irrigation techniques. This characteristic suggests it could be particularly effective in sandy

soils by providing a slow, continuous supply of water that matches the soil's infiltration rate, potentially minimizing deep percolation (Agbesi et al., 2025; Elmajetni et al., 2025).

While the conceptual advantages of SLECI are compelling in several investigations (Chaba et al., 2026; Malchev et al., 2025; Cukaliev et al., 2025; Osei et al., 2024; Malchev et al., 2022; Hansmann and Siering, 2018), empirical data on its performance relative to established high-efficiency systems like drip irrigation, especially for perennial herbs under extreme sandy soils is scarce. This study, therefore, aimed to provide a direct comparative evaluation of SLECI, surface drip, and sub-surface drip irrigation. The objectives were to quantify and compare these three systems in terms of (1) fresh yield of lavender and rosemary, (2) seasonal irrigation water consumption, and (3) irrigation water productivity (IWP), with a particular emphasis on the trade-off between biomass production and water-saving potential.

Finally, the findings of this study are expected to provide valuable insights for optimizing irrigation management and implementing effective water-saving approaches in rosemary and lavender production across similar climatic regions.

2 Methodology

2.1 Experimental site design

The study was conducted on newly established, first-year plantings of Rosemary (*Salvia rosmarinus*, Tuscan Blue variety) and Lavender (*Lavandula stoechas*, Hollandia variety) grown under open-field conditions at the Welgevallen Experimental Farm, South Bank Road, Stellenbosch, South Africa (33°56'33" S, 18°51'52" E). The experiment was carried out during the period from 1 November 2023 to 1 February 2024, corresponding to the hot-dry summer season in the region. For the experimental trial, a rectangular block 20 m long and 24 m wide was laid out, giving a cultivated area of 480 m². Within this block the three irrigation treatments formed the backbone of the design: (i) the self-regulating, low-energy, clay-based irrigation (SLECI) system installed below the surface (20 m long line with clay tubes installed below the surface), (ii) a conventional drip irrigation (20 m long drip line installed on soil surface), and (iii) a sub-surface drip irrigation (20 m long drip line installed with arrow drippers below surface) (Figure 1).

Each irrigation treatment consisted of four crop rows. Within each row, plants were arranged in an intercropping sequence of rosemary and lavender, subdivided into five measurement segments (blocks) per row, each approximately 4 meters in length, resulting in 20 measurement segments units per irrigation treatment. Plants were spaced at 20 cm within rows to accommodate their shrub growth habit, while the distance between rows was approximately 2 meters.

The experiment was established as a field-scale strip trial, with each irrigation method applied as a whole irrigation strip. For statistical analysis of the observed traits, the 20 measurement segments within each treatment strip were aggregated into three composite groups, using the same rule for all treatments and crops. Water use for each irrigation treatment was monitored using one

flowmeter per treatment. Therefore, the measurements of seasonal irrigation water consumption were considered a treatment-level values and were summarized descriptively.

2.2 Data collection, calculations and statistical analyses

The irrigation water quantity applied to each treatment was continuously monitored using flow meters. Soil moisture content was logged at a 30 cm depth using soil-moisture sensors to show soil moisture dynamic through the profile. At the conclusion of the 3-month experimental period, the above-ground biomass of all lavender and rosemary plants in each plot was harvested to determine the total fresh weight yield.

Fresh marketable yield was analyzed separately for rosemary and lavender using the three composite groups per irrigation treatment. For each crop treatment means, standard deviations, standard errors and coefficients of variation were calculated. One-way analysis of variance was performed on composite group yield values in order to compare the response of the crops to different irrigation treatments within the present field layout. Treatment means were compared by using Tukey HSD pairwise comparisons.

Water saving relative to conventional surface drip irrigation was calculated as:

$$\text{Water saving (\%)} = \frac{\text{Water use}_{\text{surface drip}} - \text{Water use}_{\text{treatment}}}{\text{Water use}_{\text{surface drip}}} \times 100 \quad (1)$$

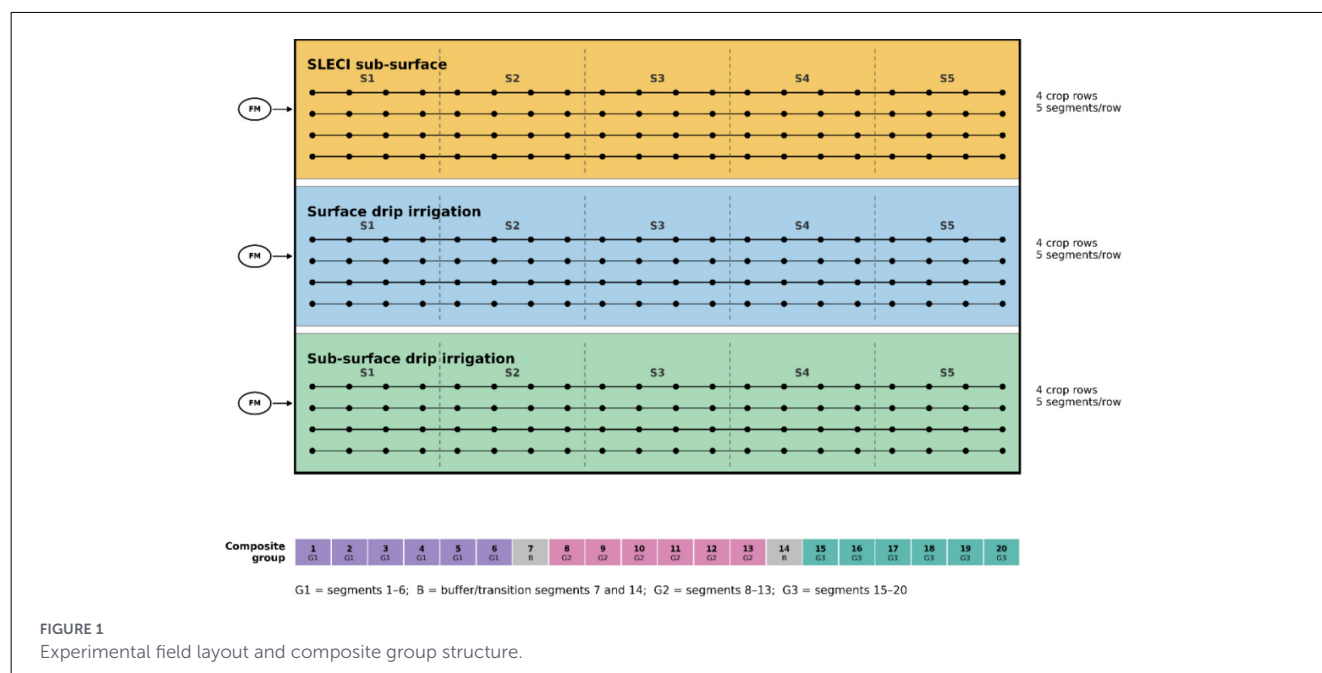
Irrigation water productivity (IWP), which measures the mass of crop produced per unit of irrigation water (Fernández et al., 2020; Cetin and Kara, 2019), was calculated as follows:

$$\text{IWP} = \frac{Y_a}{I_{wa}} \quad (2)$$

Where IWP is irrigation water productivity in kg/m³, Y_a is cropping yield in kg/ha, while I_{wa} is irrigation water applied, expressed in m³/ha. As irrigation water use was measured once per treatment, IWP was treated as a calculated treatment-level indicator and the values were compared using calculated values, percentage change and response ratios relative to surface drip irrigation.

Plant height and plant diameter were analyzed separately for both rosemary and lavender using repeated-measures mixed models. Irrigation treatment, days after transplantation (DAT), and the treatment x DAT interaction were included as fixed effects, in order to evaluate whether growth trajectories differed between the irrigation treatments over time. The composite group was used as the repeated observational unit. DAT was treated as a categorical factor because measurements were taken at four discrete time points, 1 days, 30 days, 61 days, and 92 days after transplantation (DAT).

Net growth increase was calculated for each crop, trait and treatment following the formula: growth increase = final value at 92 DAT—initial value at 1 DAT. Additionally, the cumulative growth was summarized by using the area under the curve for growth



(AUCg), calculated across the four measurement dates (Rodriguez, 2023). Growth increase and AUCg were used as complementary indicators of seasonal growth performance.

Model assumptions were evaluated before interpretation of the statistical results. For one-way ANOVA of fresh marketable yield, the residual normality was checked (Shapiro-Wilk test) and the homogeneity of variances was assessed (Levene's test). For the repeated-measures model for plant height and diameter, model adequacy was evaluated by visual inspection of residual versus fitted plots and Q-Q plots. No major deviations from model assumptions were detected.

All statistical analyses were performed by using the statistical software R 4.3.3 (R Core Team, 2023).

2.3 Climate conditions and soil characteristics

The average monthly temperature during the vegetation period (three active months) varied from 20.12 °C and 20.96 °C in November and December 2023, up to 23.89 °C in January 2024. Data for average monthly relative air humidity are in range from 62.1% for December 2023 and January 2024 up to 67.2% for November 2023. Total precipitation was 10.7 mm in November 2023 and 5.60 mm in January 2024, while no rainfall was recorded in December. The average ETo in treatments for November and December 2023 and for January 2024 were 4.48 mm, 3.85 mm, and 3.52 mm, respectively.

According to the climate condition presented in Table 1, it can be concluded that additional irrigation is needed for stable lavender and rosemary yield. Although both herbs tolerate moderate drought, their critical growth stages and responses to water stress differ. Lavender shows an interesting response to water deficit. Mild stress can intensify essential oil concentration, yet severe stress reduces stem length and makes mechanical

harvesting difficult. Lavender is most sensitive from bud formation through bloom. Therefore, crop needs a gentle but regular trickle of water during these stages. Despite natural drought tolerance, lavender can still benefit from controlled irrigation, which has been shown to enhance yield and oil concentration (Yetik and Sen, 2025). According to Saunier et al. (2022), optimizing irrigation schedules during key phenological stages, such as pre-flowering and flowering, is crucial for lavender. Rosemary naturally resists moderate drought, but its plants demonstrated the best performances when irrigation was more frequent; vice versa, the greatest percent content in essential oil was obtained when irrigation events were less frequent (La Bella et al., 2021). Akçay et al. (2023) reported that the crop evapotranspiration in lavender varied between 144–739 mm according to treatments and used method of ET analysis. Ghamarnia et al. (2022) presented average water requirement of the rosemary plant of 486 mm.

Despite the very dry weather during the vegetation period, the soil's low water retention capacity further affects the dry season. The soil at the experimental site is characterized by a high percentage of sand and little organic matter. Laboratory analyses show that 92% of the mineral fraction is sand, only 4% is silt, and 4% clay (Table 2). According to texture classification (USDA-NRCS, 2025), the soil at experimental trial is classified as sandy. In such soils, water applied by irrigation or during precipitation quickly infiltrates and seeps downwards, and the topsoil dries out quickly. With such low water-holding capacity, frequent irrigation with low water portions is better than infrequent irrigation with large portions. The pH of 7.9 places the soil in the mildly alkaline range. Both crops tolerate—indeed, rosemary often prefers—such conditions, yet some micronutrients (iron, manganese, and zinc) become less soluble. Electrical conductivity in the analyzed soil of the experimental trial is just 0.123 dS/m. According to the classification of soil based on the electrical conductivity (EC) classification supplied by Durand (1983), soil at the field trial is non-saline, meaning there is no salinity hazard.

TABLE 1 Monthly average air temperature (°C), monthly average relative humidity (%), monthly precipitation (mm) and monthly average ETo (mm).

Month	Average temperature (°C)	Average relative air humidity (%)	Precipitation (mm)	Average ETo (mm)
November 2023	20.12	67.2	10.7	4.48
December 2023	20.96	62.1	0.0	3.85
January 2024	23.89	62.1	5.60	3.52

TABLE 2 Chemical and physical characteristics of the experimental soil (0–60 cm).

Parameter	Value
pH (H ₂ O)	7.87
Electrical conductivity (dS/m)	0.123
Organic matter (%)	0.347
Available nitrogen (mg/100 g soil)	0.8
Sand (%)	92
Silt (%)	4
Clay (%)	4

3 Results

3.1 Effect of irrigation techniques on fresh rosemary and lavender marketable yield

The results presented in Figure 2 for fresh marketable rosemary leaves yield in 1 year of vegetation (after transplanting) show different responses of the same young crop because of the applied irrigation methods. When the self-regulating clay lines (SLECI) were the only source of water, the rosemary produced the lowest fresh marketable yield (282 kg per hectare). Under conventional surface drip irrigation, the fresh marketable rosemary leaves yield increased (781 kg/ha), while the highest yield (906 kg/ha) was obtained under sub-surface drip irrigation.

Lavender showed a different response pattern. The highest fresh marketable lavender yield was obtained under the surface drip irrigation treatment with 3625 kg/ha, followed by 2188 kg/ha under sub-surface drip irrigation treatment, whereas the lowest yield of 782 kg/ha was obtained under SLECI. The Both crops showed lower fresh biomass production under SLECI, the sub-surface drip treatment was the most favorable for rosemary yield, while surface drip resulted in highest lavender yield.

Based on the ANOVA applied to the composite groups per treatment, the irrigation method had a significant effect on the fresh marketable yield in both rosemary and lavender (Table 3).

3.2 Soil water dynamics and irrigation water use

According to the data for soil moisture dynamics (content) presented in Figure 3, it can be concluded that in all 3 months the highest oscillations were recorded under the treatment with conventional surface drip irrigation, followed by sub-surface drip

irrigation, while the smallest oscillations were recorded under SLECI treatment, where the least water was actually applied. This indicates that SLECI provided more gradual water release, although with substantially lower total application of water.

The results about irrigation water use during the first vegetation season in the experimental trial are presented in Table 4. Irrigation records show a different use of water between the irrigation treatments during the season. The SLECI system delivered only 533.2 m³/ha over the 3-month period. In stark contrast, the surface drip system used 6800 m³/ha, while the sub surface drip irrigation treatment ranged between the SLECI and surface drip treatment with 3060 m³ used water per hectare. Relative to surface drip irrigation, SLECI reduced irrigation water use by 92.2% and sub-surface drip irrigation by 55.0%, meaning that surface drip method used approximately 12.8 times more water than SLECI, while sub-surface drip method used approximately 5.7 times more water than SLECI.

3.3 Irrigation water productivity

Irrigation-water productivity is a simple ratio of crop yield for every cubic meter of water applied. Unlike absolute yield, which rewards sheer tonnage, water-productivity highlights how efficiently a production system turns a scarce water resource into food or other agricultural product. It is often expressed to emphasize maximizing crop production under water constrained conditions (Ali and Talukder, 2008), but also, to compare irrigation techniques or irrigation methods used in agricultural production (Gang Wang et al., 1998).

The results for irrigation water productivity for fresh marketable rosemary leaves and fresh lavender under SLECI, surface drip and sub-drip irrigation are presented in Table 5 and Figures 4 and 5. When the fresh marketable rosemary yield was divided by the season's irrigation volume, the self-regulating clay tubes (SLECI) reached the highest calculated IWP, with 0.529 kg/m³, more than four and a half times in comparison by the surface drip irrigation treatment (0.115 kg/m³). The sub-surface drip irrigation treatment reached 0.296 kg/m³, which corresponds to 2.58 times the IWP of surface drip irrigation. This indicates that despite the lower absolute rosemary yield than the drip irrigation methods, SLECI converted more efficiently each cubic meter of applied irrigation water into fresh biomass. Comparing the drip irrigation methods, the sub surface drip irrigation treatment shared the advantage of its installation in the soil in comparison with the surface drip irrigation treatment.

At the lavender experimental sites, SLECI also showed the highest calculated IWP for lavender yield, with 1.467 kg/m³, 2.7

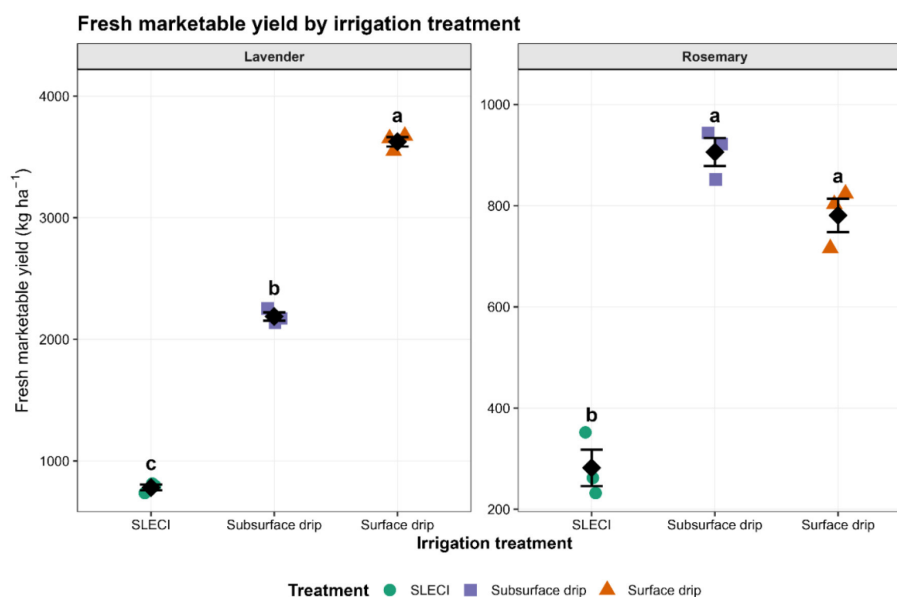


FIGURE 2

Fresh marketable yield of rosemary and lavender under different irrigation treatments (colored points represent the composite groups, black diamonds represent mean value $\pm$ SE). Different letters within the same crop indicate significant differences between irrigation treatments at p -value of 0.05.

TABLE 3 One-way ANOVA for fresh marketable yield.

Crop	Source	df	Sum Sq	F-value	p-value
Rosemary	Irrigation treatment	2	654,002	103.41	<0.001
	Residuals	6	18,974		
Lavender	Irrigation treatment	2	12,124,454	1,859.39	<0.001
	Residuals	6	19,562		

TABLE 4 Irrigation water use by treatment.

Treatment	Irrigation water use (m ³ /ha)	Water saving relative to surface drip (%)	Water-use ratio relative to surface drip
SLECI sub-surface	533.2	92.2	0.08
DRIP surface irrigation	6,800	0	0
DRIP sub-surface irrigation	3,060	55.0	0.45

times the value obtained under drip irrigation (0.533 kg/m³). The sub-surface drip irrigation delivered 0.715 kg/m³, or 1.34 times the value of surface drip irrigation. These results show that SLECI had the highest advantage of water productivity, while sub-surface drip was placed in the intermediate stage, conserving water while maintaining higher biomass production than SLECI.

Overall, the IWP results demonstrate a clear trade-off between the absolute fresh yield and irrigation water productivity. Both drip

methods produced higher fresh biomass, depending on the crop, while SLECI system used substantially less water and therefore achieved the highest calculated IWP in both rosemary and lavender.

3.4 Effect of irrigation techniques on plant diameter and height in rosemary and lavender crops

Plant diameter and height of both rosemary and lavender were measured at four time points: 1 days, 30 days, 61 days, and 92 days after transplantation (DAT). The obtained results are shown in Figure 6 and the repeated-measures model results are summarized in Table 6.

In lavender, plant diameter was different among the irrigation treatments during the experimental period. At the initial measurement, SLECI and sub-surface drip had similar values, whereas surface drip had much lower values. During the later measurements, the strongest diameter enlargement was observed under sub-surface drip method. At the final measurement, the highest lavender plant diameter was recorded under sub-surface drip irrigation (400.3), followed by surface drip (340.0) and SLECI (300.0). The plant height in lavender strongly increased under

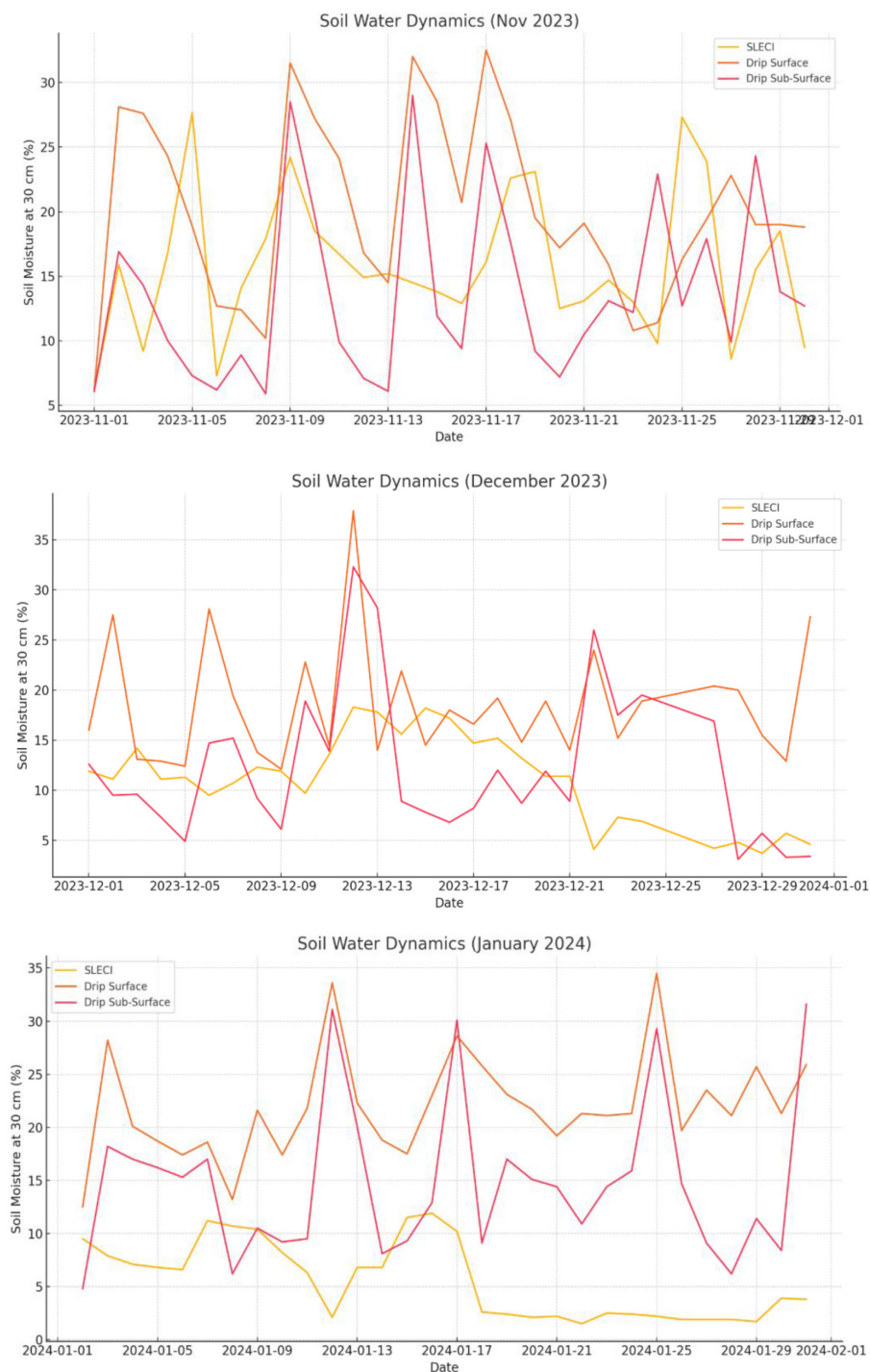


FIGURE 3

Soil water dynamics (content) for November and December 2023 and January 2024, measured by installed soil sensors at 0–30 cm.

all treatments. At the final measurement, the surface drip and sub-surface drip produced similar final plant height (350.0 mm and 349.7 mm, subsequently), higher than SLECI (310.3 mm).

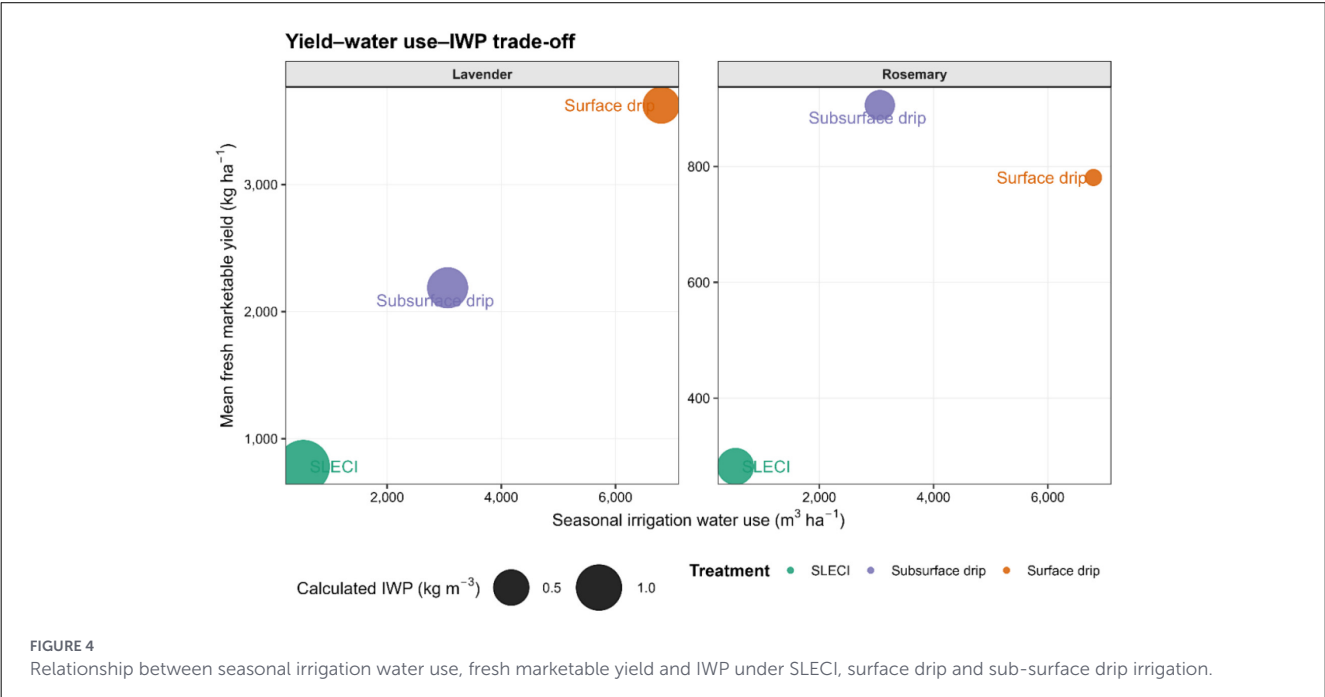
In rosemary, both plant diameter and height were also affected by the irrigation treatment. During the early growth stages, SLECI produced higher diameter than the two drip treatments, but in the final measurement sub-surface drip irrigation resulted in largest

diameter (239.7 mm), followed by SLECI (190.3 mm) and surface drip (170.0 mm). The highest plant height was also achieved with sub-surface drip irrigation (450.3 mm), followed by sub-surface (349.7 mm) and SLECI (320.3 mm).

The repeated-measures model showed significant effects of the irrigation treatment, DAT and treatment $\times$ DAT interaction on diameter and height in both crops (Table 6), indicating that

TABLE 5 Fresh marketable yield, seasonal use of irrigation water and irrigation water productivity (IWP) of rosemary and lavender under different irrigation treatments.

Crop	Treatment	Fresh marketable yield (kg/ha)	Irrigation water use (m ³ /ha)	IWP (kg/m ³)	IWP ratio relative to surface drip
Rosemary	SLECI sub-surface	282	533.2	0.529	4.60
	DRIP surface irrigation	781	6,800	0.115	1.00
	DRIP sub-surface irrigation	906	3,060	0.296	2.57
Lavender	SLECI sub-surface	782	533.2	1.467	2.75
	DRIP surface irrigation	3,625	6,800	0.533	1.00
	DRIP sub-surface irrigation	2,188	3,060	0.715	1.34



the irrigation treatments differed not only in the final plant diameter and height, but also in its growth trajectories over time. To further summarize the seasonal growth response, net growth increase and cumulative growth were calculated and presented in [Figures 7, 8](#). Net-growth increase confirmed the final growth pattern, with sub-surface drip generally producing the highest increase, particularly for rosemary height and diameter and lavender diameter. The AUCg analysis showed the same trend, indicating greater cumulative growth under sub-surface drip for the main growth traits.

4 Discussion

The results show that both drip irrigation methods produced substantially higher fresh marketable yield of rosemary and lavender in comparison with SLECI. The explanation is that surface drip supplied far more water than SLECI. SLECI used only a thirteenth of the water applied by surface drip and wetted the soil slowly. That thrift preserved plant through the dry summer

but limited a fresh-herb harvest. Similarly, [Malchev et al. \(2025\)](#) reported that drip irrigation achieved higher average yields than SLECI, probably due to supplying more water to deeper soil layers. Results from similar field experiments within the DIVAGRI project shows yield reductions in shallow rooted crops such as cowpea, while combined results were obtained in moringa crop. In addition, SLECI irrigation delivers higher fresh and dry maize yields than surface drip systems and performs as well as or better in tomato, gem-squash and bell pepper, especially when emitters are placed at shallow depths (Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project, 2025; [Osei et al., 2024](#)). Broader studies on related porous-ceramic emitter systems (SICE) also demonstrate agronomic advantages over surface and subsurface drip irrigation, including increased yields in greenhouse melons, wolfberry, and apple ([Han et al., 2025, 2023; Cai et al., 2021](#)).

Generally, the lower yields observed in this study are partly attributable to the use of newly established, first-year plants, which have not yet reached their full productive potential. In addition, the underperformance of SLECI in terms of yield can be largely attributed to the experimental site's extremely sandy soil (92% sand). [Malchev et al. \(2022\)](#) noted that the effectiveness of SLECI

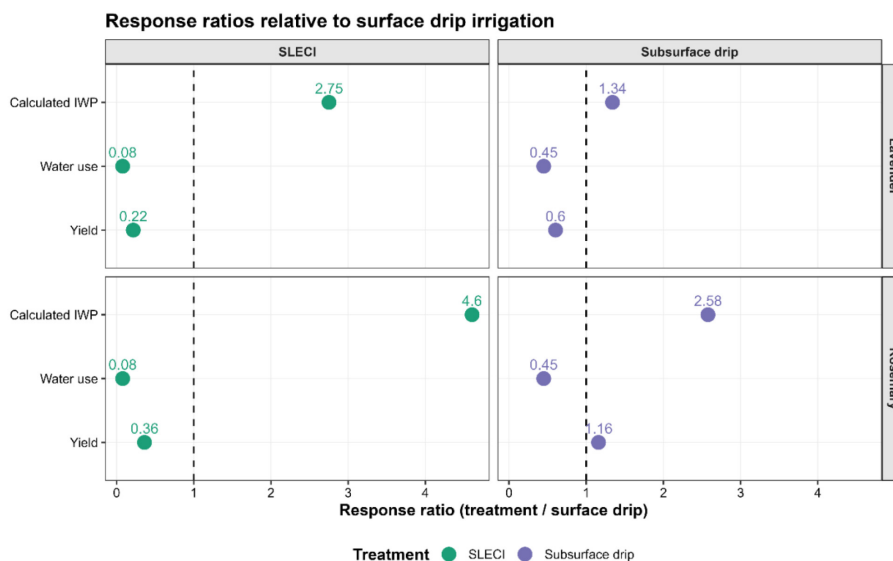


FIGURE 5

Yield, water use and IWP response ratios relative to conventional surface drip irrigation. The dashed line represents the surface drip reference value of 1.

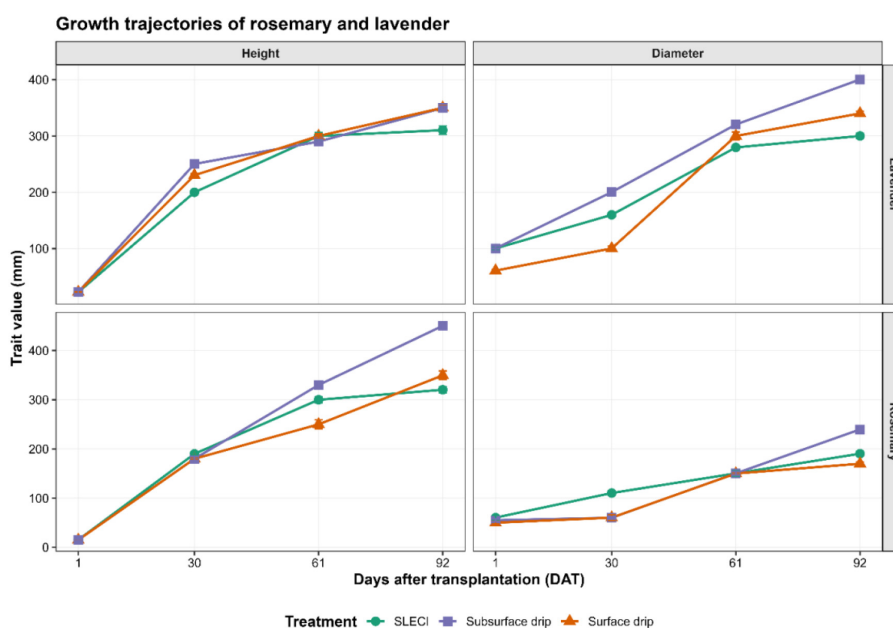


FIGURE 6

Plant height and diameter dynamics of rosemary and lavender.

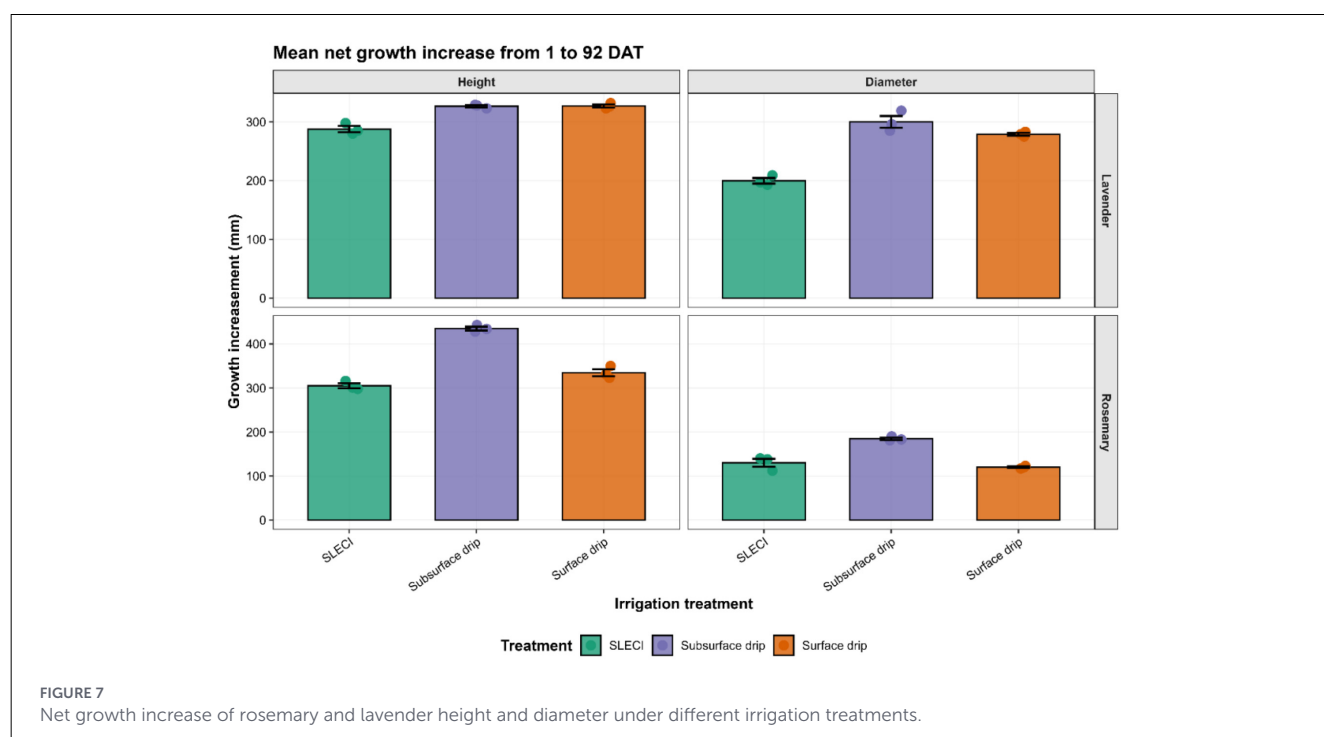
in their sweet cherry trial was likely reduced by the sandy nature of their test field. A laboratory study by Osei et al. (2025) investigating SLECI in different soil textures provides a compelling explanation. They found that while the hydraulic conductivity of the SLECI emitter was highest in sandy soil, the resulting wetting perimeter was the smallest compared to loam and clay soils. This suggests that in our sandy soil, water from the emitters moved rapidly downward due to gravity with limited lateral spread. This would create a narrow, deep wet column, failing to supply a sufficient volume of the root zone and leading to plant water stress, even though

water was being supplied continuously. Salata et al. (2020) have observed that under fully irrigated conditions, yield of fresh and air-dried lavender leaves and essential oil content were increased. Other research on deficit irrigation in lavender shows that while the crop is drought-tolerant, plant growth-related parameters and yields decline under water stress (Chrysargyris et al., 2016). Drug herb yield and yield components were negatively influenced by decreasing water levels (Akçay et al., 2023). Similarly, a study on rosemary showed that reducing irrigation to 50% of the plant's water requirement was not recommended due to

TABLE 6 Repeated-measures analysis of plant height and diameter in rosemary and lavender.

Crop	Trait	Effect	df*	Sum Sq	Mean Sq	F-value	p-value
Lavender	Diameter	Irrigation treatment	2, 6	7,255.33	3,627.67	80.38	< 0.001
		DAT	3, 18	400,528.20	133,509.40	2,958.35	< 0.001
		Treatment × DAT	6, 18	15,374.44	2,562.41	56.78	< 0.001
	Height	Irrigation treatment	2, 6	272.90	136.45	8.49	0.018
		DAT	3, 18	525,480.44	175,160.15	10,903.34	< 0.001
		Treatment × DAT	6, 18	4,314.39	719.06	44.76	< 0.001
Rosemary	Diameter	Irrigation treatment	2, 6	628.82	314.41	12.06	0.0079
		DAT	3, 18	120,431.55	40,143.85	1,539.61	< 0.001
		Treatment × DAT	6, 18	9,850.61	1,641.77	62.97	< 0.001
	Height	Irrigation treatment	2, 6	2,149.80	1,074.90	29.96	< 0.001
		DAT	3, 18	649,328.21	216,442.74	6,032.47	< 0.001
		Treatment × DAT	6, 18	23,838.94	3,973.16	110.74	< 0.001

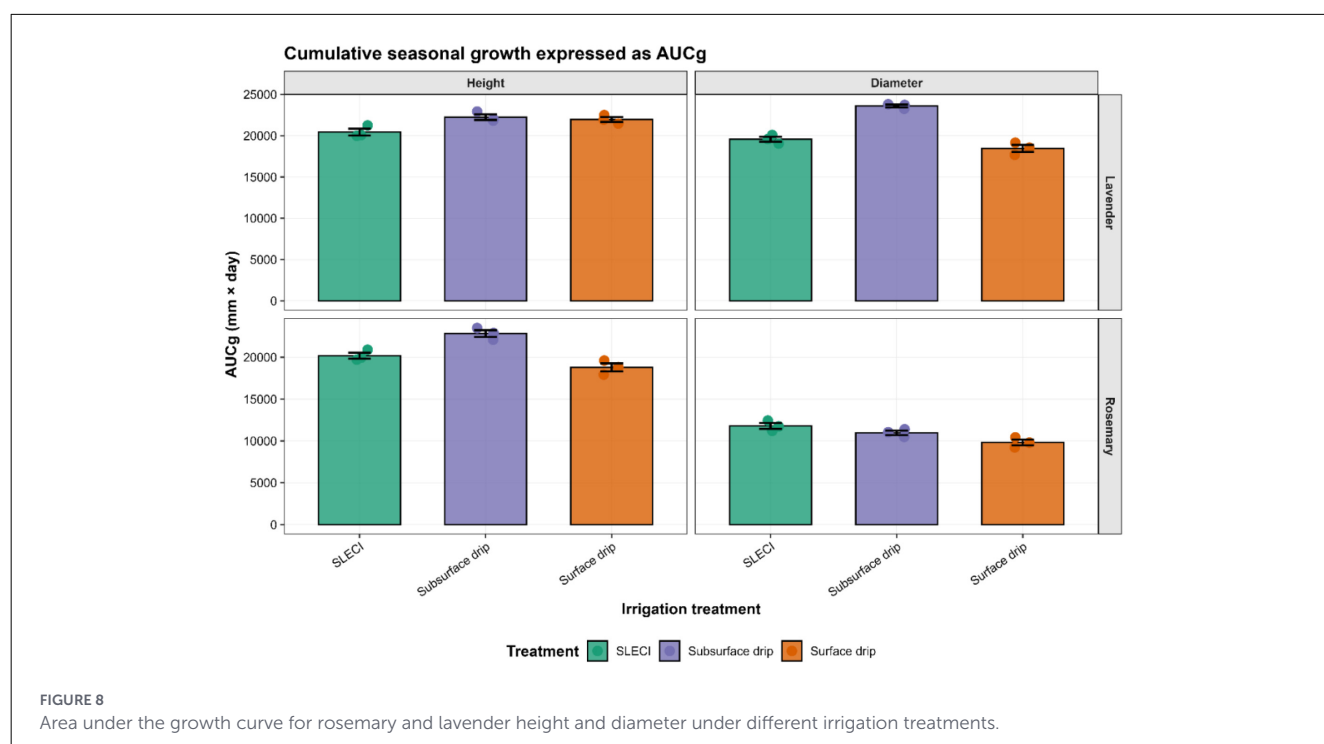
*df are shown as numerator and denominator degrees of freedom.



significant reductions in yield parameters (Ghamarnia et al., 2022). Furthermore, other evaluation of rosemary under different water stresses has shown significant positive effects on the quantity and quality of the resulting (Sarmoum et al., 2019). This confirms that while aromatic herbs are resilient, their productivity is directly linked to water availability. Omer et al. (2020) stated that the use of surface or underground micro-drip irrigation systems does not exert a significant effect on the characteristics of rosemary plants. Another study demonstrated that the interval of time between irrigation events significantly influenced the characteristics of rosemary (La Bella et al., 2021).

On the other hand, our findings for soil moisture content (dynamic) are in agreement with other research where SLECI was compared with surface and subsurface drip irrigation. Field monitoring within DIVAGRI H2020 project shows that SLECI

maintains more stable soil moisture in moringa and cowpea than surface drip during hot, dry spells, as well as in tomato and maize crops during the vegetation (Chaba et al., 2026; Cukaliev et al., 2025; Technical Report on SLECI pilot sites installed within the DIVAGRI Project, 2025). Furthermore, in similar research technology, the variations in soil water contents for subsurface irrigation with ceramic emitter's (SICE) were smaller than those for sub-surface drip irrigation SDI (Cai et al., 2021). According to Xu and Hsiao (2004), available water in the soil profile and water use efficiency determines the plant productivity. Sałata (2020) reported that in the cultivation of *L. angustifolia* soil moisture content is one of the factors that may affect yield and raw material chemical composition. Lower soil moisture content reduced the leaf area, leaf number, and fresh and dry weights of shoots in two different English lavender cultivars (Zhen and Burnett, 2015;



Gitelson et al., 2003; Sonobe and Wang, 2017). The findings of the study in terms of WUE and IWUE shows the sensitivity of the green herb yield of lavender to soil moisture (Akçay et al., 2023).

SLECI's system is designed to respond to plant root demand, delivering water only when suction forces from drying soil trigger release. The result is a slow, steady seep that matches plant demand while keeping the soil surface almost dry (Malchev et al., 2025; Mahler, 2024). In practical terms, the obtained results for water use in our research illustrate different possibilities for water use in rosemary and lavender crop production. Similarly, our results corresponded with those presented across multi crop investigation, where SLECI was compared with drip irrigation in sweet cherry, maize, moringa, cowpea, gem squash and tomato (Chaba et al., 2026; Malchev et al., 2025; Cukaliev et al., 2025; Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project, 2025). Our results for water use are lower than those in the literature, primarily due to the fact that it concerns the 1 year of vegetation for both crops. In deficit irrigation studies under semi-arid conditions, Akçay et al. (2023) reported irrigation application amounts from 197.0 mm to 633.0 mm for lavender cultivation, while Ghamarnia et al. (2022) in rosemary experiments noted from 473 mm to 498 mm. Additionally, Yetik and Sen (2025) in their study with deficit irrigation showed irrigation water amounts from 325.5 mm to 1162.4 mm, while Noorollahi et al. (2016) reported seasonal ET for lavender reaching up to 1191.4 mm.

Irrigation is a valuable agricultural technology, its profitability and long-term sustainability depend on proper management practices that enhance efficiency, lower operating costs, and minimize environmental impacts (Ali and Talukder, 2008; de Lacerda and de Oliveira, 2007). Since water availability limits agricultural production in many regions, improving yields with less water is essential. Consequently, improving the amount of crop produced per unit of water has become a fundamental requirement

for sustainable agriculture, especially given that farming accounts for roughly 70% of global freshwater use (FAO, 2023). The results in our study present a clear trade-off between maximizing crop biomass and optimizing water use efficiency in a challenging agricultural setting. The SLECI system's performance underscores both its profound potential for water conservation and the critical need to tailor its design to specific environmental conditions. Our experimental results demonstrate that calculated irrigation water productivity (IWP), an important criterion for assessing agricultural sustainability and efficiency, showed clear differences among the irrigation treatments applied across the experiment. The obtained results are in agreement with findings with other different crops as maize, tomato, gem squash, cowpea and moringa (Chaba et al., 2026; Cukaliev et al., 2025; Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project, 2025), where SLECI treatments showed better IWP compared than surface or subsurface drip irrigation with different crops established across Africa. In other study with sweet cherry field experiments, the average water productivity in case of SLECI irrigation is more than 12 times higher compared with the average IWP for drip irrigation. The apparent water-productivity advantage stems from two factors: first, SLECI delivered only the water that root tension demanded, and second, there is almost no loss of water to evaporation and deep percolation (Malchev et al., 2025). Results from our report showed that sub surface drip is more productive than surface drip irrigation, mainly due to advantage of drip line installation in the soil in comparison with the surface drip irrigation treatment, similarly like in results presented by Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project (2025) and results reported by Malchev et al. (2025). Additionally, Osei et al. (2025) in their investigation with bell pepper crop presented better water use efficiency of SLECI irrigation lines in burying depth of 15 cm compared lower depth (5 cm and 10 cm). Across

studies in apples (Cai et al., 2021), wolfberry (Han et al., 2023), and melon (Han et al., 2025), subsurface irrigation with ceramic emitters (SICE) consistently outperformed drip and subsurface drip irrigation, providing measurable improvements in water use efficiency and overall water productivity for each crop. In addition, our findings are consistent with recent experimental and meta-analytical studies showing that optimizing irrigation practices and resource inputs can substantially improve water productivity, even when yield responses are variable or moderately reduced under constrained conditions (Zhang et al., 2024, 2025). Despite the low fresh marketable yield, the IWP of the SLECI treatment in our investigation are relatively high. SLECI, functioning almost as a plant-controlled water system, showed the highest calculated conversion of applied irrigation water into fresh plant biomass. Additionally, the consistency of these findings with broader deficit irrigation literature suggests that the observed performance of SLECI is not solely system-specific but also reflects general plant responses to limited water availability. This observed trade-off between reduced yield and increased irrigation water productivity is consistent with findings from deficit irrigation studies under comparable agro-climatic conditions. Sezen et al. (2023) reported that although vegetative growth in *Salvia splendens* was reduced under deficit irrigation, plants exhibited improved water-use efficiency, reflecting a similar shift toward resource optimization. Furthermore, Sezen et al. (2024) showed that *Antirrhinum majus* adapted to limited water supply by reducing growth intensity while maintaining physiological functionality. Such responses confirm that under water-limited environments, plants may prioritize survival and efficient resource use over maximum biomass production. In aromatic crops, this trade-off is well documented. Akçay et al. (2023) demonstrated that in lavender, moderate deficit irrigation strategies can significantly increase water productivity while maintaining relatively stable yields, supporting the patterns observed in the present study.

In a study, four levels of irrigation (100, 85%, 70%, and 55%) were applied to rosemary and the results showed that treatment with 85% saved 348 m³ of water and increased water use efficiency by 11.3% compared to treatment 100% of irrigation (Rigi Karvandri et al., 2020). In other research, deficit irrigation reduced seed yield, biological yield and water use significantly, but water use efficiency (WUE) was significantly increased in Isabgol and French psyllium (Rahimi et al., 2011). The findings of Yetik and Sen (2025) emphasize that improving water productivity through moderate to severe deficit irrigation strategies can support sustainable lavender production under semi-arid conditions, even when absolute yields are partially compromised. Results indicated that treatment with moderate deficit (33% water deficit) is recommended for optimizing water productivity with minimal yield reduction. However, in water-limited regions, 66% water deficit provided viable productivity, offering a suitable balance for sustainable lavender production in semi-arid climates. Similar results are reported by Singh (2004) in rosemary crops with moderate soil moisture regime. For growers who sell essential oil rather than fresh biomass, that water-sparing trait could offset the smaller mass because oil content often rises under mild stress (Yetik and Sen, 2025; Pirzad and Mohammadzadeh, 2018). La Bella et al. (2021) found that less frequent irrigation of potted

rosemary led to the highest percentage of essential oil. On the other hand, the results from the other study showed that water stress, especially when occurring over a long period of time, could reduce the essential oil yield (in addition to the decrease in floral biomass production), but also alter its quality (Chrysargyris et al., 2016). In the study of Ghamarnia et al. (2022), irrigation at 75% and 50% of the rosemary plant's water requirement produced similar essential oil yields (0.3 cm³/plant), while full irrigation achieved the highest yield (0.4 cm³/plant). This indicates that the reduction of water requirement from 100% to 75% has a direct effect on the amount of essential oil. However, there are no significant differences in the essential oils of 75% and 50% water requirements, but this difference was significant in the treatment of 25% of water requirement. For dry matter production, 75% irrigation is acceptable, but full irrigation is necessary for maximum essential oil yield.

Overall, our results at the harvest time showed that rosemary responded best to subsurface drip and SLECI irrigation, with greater plant diameter than under conventional surface drip, while lavender performed better under subsurface and surface drip than with SLECI. In contrast, crops such as maize, tomato, moringa, cowpea and pepper showed more mixed or crop-specific responses on SLECI irrigation in other research studies. In Technical Report on SLECI pilot sites installed within the DIVAGRI Project (2025), irrigation techniques show very small variation between the maize irrigation treatments. Namely, subsurface SLECI irrigation treatments show better results for plant height (186.3 cm) in comparison with surface SLECI (185.7 cm) and conventional surface drip irrigation treatment (185.2 cm). SLECI produced smaller plants and thicker stems in tomato crops, reported Cukaliev et al. (2025). In addition, SLECI and drip irrigation had no significant effect on the height of the moringa, while significant differences were recorded on sole cowpeas with taller plants under a subsurface irrigation system. Moringa and cowpea generally exhibited thicker stems under SLECI (Chaba et al., 2026). In the study with bell peppers (Osei et al., 2025), the best growth parameters were achieved with a burying depth of SLECI lines at 10 cm and 80% recommended application fertilizer dosage. This combination resulted in the highest plant height and leaf area. Together, these comparisons indicate that rosemary aligns more closely with crops benefiting from SLECI or subsurface irrigation, whereas lavender behaves more like tomato in showing limited or weaker positive response to SLECI. La Bella et al. (2020) reported significant differences in plant height and diameter and better results in 2 days irrigated rosemary in comparison with 4 days. In other study, full irrigation in the subsurface drip method caused the highest plant height and the results showed that irrigation at 75% of the water requirement in the subsurface irrigation method caused a 32.3% reduction in plant height compared to full irrigation (Asadi et al., 2019). Plant height has also been significantly affected by deficit irrigation. The maximum average plant height obtained in 100% and 25% irrigation is 40 cm and 14 cm, respectively (Ghamarnia et al., 2022). Additionally, an observed decrease in plant height, stem diameter, leaf length, and fresh biomass of lavender is associated with increasing water deficit (Chrysargyris et al., 2016). Yetik and Sen (2025) in their study with deficit irrigation showed clear irrigation-

related differences in plant diameter during the early years, with fully irrigated plants outperforming rain-fed ones, and the 66% water deficit treatment matching full irrigation. However, by 2022 these differences disappeared, indicating the crop's growing adaptation to water-limited conditions. Plant height followed a similar pattern: 100% (full irrigated), 33% and 66% water deficit, consistently produced comparable and taller plants, while the rain-fed treatment remained significantly shorter across most years. Overall, lavender demonstrated resilience under moderate water stress but remained sensitive to complete lack of irrigation. In addition, different irrigation water levels influenced the green herb yield, drug herb yield, drug leaf yield and plant height of purple basil (Ekren et al., 2012; Palta, 1990; Croft et al., 2017). The yield, main stem length, and main stem weight of dill plants exposed to three different irrigation levels showed a significant change at $p < 0.001$ (El-Zaeddi et al., 2017).

4.1 Pathways for system optimization

The study's findings do not invalidate the SLECI technology itself but rather point to a mismatch between the system's configuration and the site's conditions. The solution lies in increasing the water delivery rate to a level that supports productive growth without sacrificing efficiency. This can be achieved through several engineering and agronomic adjustments. The field report recommends closer spacing of plants to the emitters, but a more scalable solution involves redesigning the irrigation layout. This could include reducing the distance between individual clay emitters along the lateral line or installing multiple parallel SLECI lines per crop row to enlarge the total wetted volume. Another crucial avenue for optimization is modifying the emitters themselves. Elmajetni et al. (2025) conducted a hydraulic characterization of different SLECI emitters, showing that discharge rates vary based on clay properties and operating pressure. Similar research results are presented. Selecting emitters with higher hydraulic conductivity would be a direct way to increase water delivery and would be a key area for future research, as supported by the systematic review of clay-based technologies by Mahler (2024). According to Agbesi et al. (2025) the burial depth had a minimal effect on the emitter discharge but notably affected the advancement and time at which wetting fronts reached the soil surface and bottom boundaries. Operating the SLECI emitter at a higher operating pressure head and shallower burial depth could degrade irrigation water application and water use efficiency, reported same authors. Anyhow, future research should expand to other soil textures, rooting depths and clay dripper installation distance (in the row and in soil depth) enabling the optimal design of the SLECI system for a wider range of crops and environmental conditions.

5 Conclusion

This study showed that, in the highly permeable sandy soils of South Africa's semi-arid climate, the Self-regulating, Low-Energy, Clay-based Irrigation (SLECI) system substantially reduced

irrigation water consumption (by more than 90% compared to surface drip irrigation), but this high water-saving efficiency was accompanied by significantly lower fresh marketable yields of lavender and rosemary, with reductions reaching up to 4–5 times depending on the crop and compared to both surface and subsurface drip systems. The sub-surface drip irrigation system offered the best compromise, providing high yields with moderate water savings.

The key conclusion is that the low water delivery rate of the SLECI emitters, combined with the rapid drainage of the sandy soil, created a state of severe deficit irrigation that hindered biomass accumulation. However, the system's high calculated irrigation water productivity (IWP) highlights its water-saving potential. The path forward for making SLECI a viable production technology in such environments lies in optimizing its water delivery rate. Future research must focus on engineering solutions, such as selecting emitters with higher hydraulic conductivity and designing field layouts with closer emitter spacing, to better match the water supply with crop demand and soil hydraulic properties.

Finally, it should be noted that the results obtained from our research relate to 1-year-old lavender and rosemary, which leaves room in the following years to provide additional information on the impact of SLECI on older plantations of these crops, as well as its influence on soil–plant–water interactions. Furthermore, future studies should include independently replicated irrigation units and multi-season measurements to confirm the observed yield and water-productivity patterns.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

VT: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. HBS: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. OC: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. GW: Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. IG: Investigation, Writing – original draft, Visualization. MJ: Formal analysis, Methodology, Software, Writing – review & editing, Writing – original draft. SS: Writing – original draft, Writing – review & editing. SM: Writing – original draft, Writing – review & editing. JS: Writing – original draft, Writing – review & editing. GO: Writing – original draft, Writing – review & editing. ZD: Writing – original draft, Writing – review & editing. SN: Writing – original draft, Writing – review & editing. MM: Writing – original draft, Writing – review & editing. AS: Writing – original draft, Writing – review & editing. IS: Writing – original draft,

Writing – review & editing. HA: Software, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- Agbesi, W. E. K., Sam-Amoah, L. K., Darko, R. O., Kumi, F., and Boafo, G. (2025). Numerical models for predicting water flow characteristics and optimising a subsurface self-regulating, low-energy, clay-based irrigation (SLECI) system in sandy loam soil. *Water* 17:2058. doi: 10.3390/w17142058
- Akçay, S., Tunalı, S. P., Gürbüz, T., and Dagdelen, N. (2023). Determination of optimal deficit irrigation strategies for yield and yield components of lavender (*Lavandula angustifolia* Mill.) in semi-arid conditions. *Appl. Ecol. Environ. Res.* 21, 6023–6039. doi: 10.15666/aer/2106_60236039
- Ali, M. H., and Talukder, M. S. U. (2008). Increasing water productivity in crop production—a synthesis. *Agricu. Water Manag.* 95, 1201–1213. doi: 10.1016/j.agwat.2008.06.008
- Asadi, R., Hassan Pour, F., Mehrabani, M., Baghizadeh, A., and Karandish, F. (2019). Evaluation of quantitative traits of *Rosmarinus officinalis* L. with use of two drip irrigation systems influenced by deficit irrigation. *Iran. J. Irrigat. Drainage* 13, 1027–1038.
- Ayars, J. E., Phene, C. J., Hutmacher, R. B., Davis, K. R., Schoneman, R. A., Vail, S. S., et al. (1999). Subsurface drip irrigation of row crops: a review of 15 years of research at the water management research laboratory. *Agric. Water Manag.* 42, 1–27. doi: 10.1016/S0378-3774(99)00025-6
- Azizi, A., Yan, F., and Honermeier, B. (2009). Herbage yield, essential oil content and composition of three oregano (*Origanum vulgare* L.) populations as affected by soil moisture regimes and nitrogen supply. *Ind. Crops Prod.* 29, 554–561. doi: 10.1016/j.indcrop.2008.11.001
- Baher, Z. F., Mirza, M., Ghorbanli, M., and Rezaii, M. B. (2002). The influence of water stress on plant height, herbal and essential oil yield and composition in *Satureja hortensis* L. *Flavour Fragr. J.* 17, 275–277. doi: 10.1002/ffj.1097
- Cáceres-Cevallos, G. J., Quílez, M., Ortiz de Elguea-Culebras, G., Melero-Bravo, E., Sánchez-Vioque, R., and Jordán, M. J. (2023). Agronomic evaluation and chemical characterization of *Lavandula latifolia* Medik. under the semiarid conditions of the Spanish southeast. *Plants* 12:1986. doi: 10.3390/plants12101986
- Cai, Y., Wu, P., Zhu, D., Zhang, L., Zhao, X., Gao, X., et al. (2021). Subsurface irrigation with ceramic emitters: an effective method to improve apple yield and irrigation water use efficiency in the semiarid Loess Plateau. *Agric. Ecosyst. Environ.* 313:107404. doi: 10.1016/j.agee.2021.107404
- Çetin, Ö., and Kara, A. (2019). Assessment of water productivity using different drip irrigation systems for cotton. *Agric. Water Manag.* 223:105693. doi: 10.1016/j.agwat.2019.105693
- Cetin, O., and Kara, A. (2019). Assessment of water productivity using different drip irrigation systems for cotton. *Agric. Water Manag.* 223:105693.
- Chaba, H., Tanaskovik, V., Araya, H., Cukaliev, O., Araya, N., Steyn, M., et al. (2026). A self-regulating, low-energy, clay-based irrigation system: performance assessment in moringa and cowpea. *Sustainability* 18:1853. doi: 10.3390/su18041853
- Chrysargyris, A., Laoutari, S., Litskas, V. D., Stavrinides, M. C., and Tzortzakis, N. (2016). Effects of water stress on lavender and sage biomass production, essential oil composition and biocidal properties against *Tetranychus urticae* (Koch). *Sci. Hortic.* 213, 96–103. doi: 10.1016/j.scienta.2016.10.024
- Croft, H., Chen, J. M., Luo, X., Bartlett, P., Chen, B., and Staebler, R. M. (2017). Leaf chlorophyll content as a proxy for leaf photosynthetic capacity. *Glob. Change Biol.* 23, 3513–3524. doi: 10.1111/gcb.13599
- Cukaliev, O., Kumi, F., Tanaskovik, V., Agbesi, W. E. K., Suryadevara, S. T., Malchev, S., et al. (2025). Field evaluation of tomato crop production under SLECI irrigation. *Agricu. Forest.* 71, 145–161. doi: 10.17707/AgricuForest.71.4.09
- de Lacerda, N. B., and de Oliveira, T. S. (2007). Agricultura irrigada e a qualidade de vida dos agricultores em perímetros do Estado do Ceará, Brasil. *Revista Ciência Agronômica* 38, 216–223.
- Durand, J. H. (1983). *Les sols irrigables: Etude pédologique*. Paris: Presses Universitaires de France.
- Ekren, S., Sonmez, C., Ozcalak, E., Kurtas, Y. S. K., Bayram, E., and Gurgulu, H. (2012). The effect of different irrigation water levels on yield and quality characteristics of purple basil (*Ocimum basilicum* L.). *Agric. Water Manag.* 109, 155–161. doi: 10.1016/j.agwat.2012.03.004
- Elmajet, I., Wahid, N., Taoufik, N., Sabri, A., Krause, R., Siering, J., et al. (2025). Hydraulic characterization of Moistube and SLECI irrigation systems compared to conventional drip irrigation. *Agric. Eng. Int. CIGR J.* 27, 42–51.
- El-Zaedi, H., Tomé, J. M., Calin-Sánchez, A., Burló, F., and Carbonell-Barrachina, A. A. (2017). Irrigation dose and plant density affect the volatile composition and sensory quality of dill. *J. Sci. Food Agric.* 97, 427–433. doi: 10.1002/jsfa.7890
- FAO (2023). *The State of the World's Land and Water Resources for Food and Agriculture (SOLAW 2021): Systems at Breaking Point*. Rome: Food and Agriculture Organization of the United Nations. Available online at: <https://openknowledge.fao.org/server/api/core/bitstreams/bc8810ae-2a13-4cfe-b019-339158c7e608/content/cb7654en.html> (Accessed September 10, 2025).
- Fernández, J. E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., and Cuevas, M. V. (2020). Water use indicators and economic analysis for on-farm irrigation decision: A case study of a super high density olive tree orchard. *Agric. Water Manag.* 237:106074. doi: 10.1016/j.agwat.2020.106074

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- Gang Wang, Z., Delva, L., Gaboli, M., Rivi, R., Giorgio, M., Cordon-Cardo, C., et al. (1998). Role of PML in cell growth and the retinoic acid pathway. *Science* 279, 1547–1551.
- Ghamarnia, H., Palash, M., and Amiri, S. (2022). Deficit irrigation effects on rosemary plant (*Rosmarinus officinalis* L.) parameters in a semi-arid climate. *Agrotech. Indus. Crops* 2, 57–64.
- Gitelson, A. A., Gritz, Y., and Merzlyak, M. N. (2003). Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. *J. Plant Physiol.* 160, 271–282. doi: 10.1078/0176-1617-00887
- Guo, J., Zheng, L., Ma, J., Li, X., and Chen, R. (2023). Meta-analysis of the effect of subsurface irrigation on crop yield and water productivity. *Sustainability* 15:15716. doi: 10.3390/su152215716
- Han, M., Zhang, L., and Liu, X. (2023). Subsurface irrigation with ceramic emitters improves wolfberry yield and economic benefits on the Tibetan Plateau, China. *J. Arid Land* 15, 1376–1390. doi: 10.1007/s40333-023-0034-3
- Han, M., Zhang, L., Zhao, X., and Xie, K. (2025). Subsurface irrigation with ceramic emitters improved the water productivity and nitrogen use efficiency of greenhouse melons. *Irrig. Drain.* 74, 885–899. doi: 10.1002/ird.3084
- Hansmann, H., and Siering, J. (2018). *Verhinderung des Algenbefalls von Saugsystemen aus Ton zur Bewässerung von Nutzpflanzen in tropischen Gebieten der Sahel-Zone am Beispiel Ghanas* [Preventing algae infestation of clay suction systems for irrigating crops in tropical areas of the Sahel zone using Ghana as an example]. German Research Report on Agricultural Innovations. Available online at: <https://edocs.tib.eu/files/e01fn20/1690620927.pdf> (Accessed August 15, 2025).
- Hassan, F. A. S., Bazaid, S., and Ali, E. F. (2013). Effect of deficit irrigation on growth, yield and volatile oil content on *Rosmarinus officinalis* L. plant. *J. Med. Plants Stud.* 1, 12–21.
- Hosseini, R., and Heidari, M. (2025). Impact of drought stress on biochemical and molecular responses in lavender (*Lavandula angustifolia* Mill.): effects on essential oil composition and antibacterial activity. *Front. Plant Sci.* 16:1506660. doi: 10.3389/fpls.2025.1506660
- IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
- La Bella, S., Virga, G., Iacuzzi, N., Licata, M., Sabatino, L., Consentino, B. B., et al. (2021). Effects of irrigation, peat-alternative substrate and plant habitus on the morphological and production characteristics of Sicilian rosemary (*Rosmarinus officinalis* L.) biotypes grown in pot. *Agriculture* 11:13. doi: 10.3390/agriculture11010013
- La Bella, T., Imbeaud, S., Peneau, C., Mami, I., Datta, S., Bayard, Q., et al. (2020). Adeno-associated virus in the liver: natural history and consequences in tumour development. *Gut* 69, 737–747.
- Lakhari, I. A., Yan, H., Zhang, C., Wang, G., He, B., Hao, B. (2024). A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *Agriculture* 14:1141. doi: 10.3390/agriculture14071141
- Mahler, E. (2024). Innovations in clay-based irrigation technologies—a systematic review. *Sustainability* 16:7029. doi: 10.3390/su16167029
- Malchev, S., Kornov, G., and Hansmann, H. (2022). Innovative clay-based micro-irrigation system “SLECI” (self-regulating, low energy, clay-based irrigation): preliminary results from cherry orchard trials. *J. Agric. Food Environ. Sci.* 76, 45–55. doi: 10.55302/JAFES22765045m
- Malchev, S., Tanaskovik, V., Chukaliev, O., Germanova, D., and Kornov, G. (2025). Sweet cherry (*Prunus avium* L.) response to self-regulating low energy clay-based irrigation (S.L.E.C.I.) system. *Plants* 14:3533. doi: 10.3390/plants14223533
- Mancosu, N., Snyder, R. L., Kyriakakis, G., and Spano, D. (2015). Water scarcity and future challenges for food production. *Water* 7, 975–992. doi: 10.3390/w7030975
- Mohtar, R. H., and Fares, A. (2022). The future of water for food. *Front. Sustain. Food Syst.* 6:880767. doi: 10.3389/fsufs.2022.880767
- Noorollahi, M., Hassanli, A. M., Ghanbarian, G. A., and Taghvaei, M. (2016). Determination of crop coefficient (Kc) for *Rosmarinus officinalis* L., *Lavandula angustifolia* Mill. and *Silybum marianum* L. Gaertn as medicinal plants using water balance approach. *Iran. J. Irrigat. Drainage* 10, 117–127.
- Omer, E., Hendawy, S., El Gendy, A. N., Mannu, A., Petretto, G. L., and Pintore, G. (2020). Effect of irrigation systems and soil conditioners on the growth and essential oil composition of *Rosmarinus officinalis* L. cultivated in Egypt. *Sustainability* 12:6611. doi: 10.3390/su12166611
- Osei, G., Owusu-Sekyere, J., Sam-Amoah, L. K., Kumi, F., Hansmann, H., Agyemang, V. O., et al. (2024). Bell pepper (*Capsicum annuum*) response to self-regulating low energy clay-based irrigation (SLECI) system, burying depth and fertilizer application dosage. *J. Central Eur. Agric.* 25, 1148–1161. doi: 10.5513/JCEA01/25.4.4462
- Osei, G., Sam-Amoah, L. K., Owusu-Sekyere, J., Hansmann, H., Kumi, F., and Menash, K. (2025). Performance characteristics of self-regulating low energy clay-based irrigation system in different soil types. *J. Ghana Instit. Eng.* 25, 9–15. doi: 10.56049/jghie.v25i1.212
- Palta, J. P. (1990). Leaf chlorophyll content. *Remote Sens. Rev.* 5, 207–213. doi: 10.1080/02757259009532129
- Papadopoulos, I. (1996). ‘Micro-irrigation systems and fertigation,’ in *Sustainability of Irrigated Agriculture*, eds. L. S. Pereira, (Dordrecht: Kluwer Academic Publishers), 309–322. doi: 10.1007/978-94-015-8700-6_18
- Pejić, B., Adamović, D., Maksimović, L., and Mačkić, K. (2017). Effect of drip irrigation on yield, evapotranspiration and water use efficiency of sweet basil (*Ocimum basilicum* L.). *Ratar. Povrt.* 54, 124–129. doi: 10.5937/ratpov54-14808
- Pirzad, A., and Mohammadzadeh, S. (2018). Water use efficiency of three mycorrhizal Lamiaceae species (*Lavandula officinalis*, *Rosmarinus officinalis* and *Thymus vulgaris*). *Agric. Water Manag.* 204, 1–10. doi: 10.1016/j.agwat.2018.03.020
- R Core Team (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online at: <https://www.R-project.org/>
- Rahimi, A., Jahansoz, M. R., Hoseini, S. M., Sajjadinia, A. R., Roosta, H. R., and Fateh, E. (2011). Water use and water-use efficiency of isabgol (*Plantago ovata*) and French psyllium (*Plantago psyllium*) in different irrigation regimes. *Aust. J. Crop Sci.* 5, 71–77.
- Rigi Karvandri, A., Mehraban, A., Ganjali, H., Miri, K., and Mobser, H. (2020). Effect of quantity and quality of irrigation on quantitative traits of *Rosmarinus officinalis* L. Iran. *J. Irrigat. Drainage* 14, 402–413.
- Rodriguez, D. (2023). Area under the curve as an alternative to latent growth curve modeling when assessing the effects of predictor variables on repeated measures of a continuous dependent variable. *Stats* 6, 674–688. doi: 10.3390/stats6020043
- Salata, A. (2020). Supplementary irrigation and drying method affect the yield and essential oil content and composition of lavender (*Lavandula angustifolia* Mill.) flowers. *Acta Sci. Pol. Hortorum Cultus* 19, 139–151. doi: 10.24326/asphc.2020.6.12
- Salata, A., Buczkowska, H., and Nurzynska-Wierdak, R. (2020). Yield, essential oil content, and quality performance of *Lavandula angustifolia* leaves, as affected by supplementary irrigation and drying methods. *Agriculture* 10:590. doi: 10.3390/agriculture10120590
- Sarmoum, R., Haid, S., Biche, M., Djazouli, Z., Zebib, B., and Merah, O. (2019). Effect of salinity and water stress on the essential oil components of rosemary (*Rosmarinus officinalis* L.). *Agronomy* 9:214. doi: 10.3390/agronomy9050214
- Saunier, A., Ormeño, E., Moja, S., Fernandez, C., Robert, E., Dupouyet, S., et al. (2022). Lavender sensitivity to water stress: comparison between eleven varieties across two phenological stages. *Ind. Crops Prod.* 177:114531. doi: 10.1016/j.indcrop.2022.114531
- Sezen, I., Yaganoglu, S., Akpinar Külekçi, E., and Karahan, A. (2023). Effect of deficit irrigation on growth parameters of the *Salvia splendens* L. plant. *Water* 15:4187. doi: 10.3390/w15234187
- Sezen, I., Yaganoglu, S., Akpinar Külekçi, E., and Karahan, A. (2024). *Antirrhinum majus* bitkisinin gelişim parametreleri üzerine kisitli sulamanın etkisi [Effect of limited irrigation on growth parameters of *Antirrhinum majus* plants]. *Tekirdag Ziraat Fakültesi Dergisi* 21, 1017–1032. doi: 10.33462/jotaf.1402676
- Singh, M. (2004). Effects of plant spacing, fertilizer, modified urea material and irrigation regime on herbage, oil yield and oil quality of rosemary in semi-arid tropical conditions. *J. Hortic. Sci. Biotechnol.* 79, 411–415. doi: 10.1080/14620316.2004.11511782
- Sonobe, R., and Wang, Q. (2017). Hyperspectral indices for quantifying leaf chlorophyll concentrations performed differently with different leaf types in deciduous forests. *Ecol. Inform.* 37, 1–9. doi: 10.1016/j.ecoinf.2016.11.007
- Soria-Lopez, A., Garcia-Perez, P., Carpena, M., Garcia-Oliveira, P., Otero, P., Fraga-Corral, M., et al. (2023). Challenges for future food systems: from the green revolution to food supply chains with a special focus on sustainability. *Food Front.* 4, 9–20. doi: 10.1002/fft2.173
- Tanaskovik, V., Cukaliev, O., Kanwar, R. S., Markoski, M., and Spalevic, V. (2016). Nitrogen fertilizer use efficiency of pepper as affected by irrigation and fertilization regime. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 44, 525–532. doi: 10.15835/nbha44210415
- Tekinel, O., and Kanber, R. (2002). “Trickle irrigation experiments in Turkey,” in *Modern and Traditional Irrigation Technologies in the Eastern Mediterranean*, eds. M. Özyaz, and H. A. Biçak (Ottawa, ON: International Development Research Centre), 27–72.
- University of Ss. Cyril and Methodius in Skopje, Faculty of Agricultural Sciences and Food-Skopje (2025). *Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project, DIVAGRI Consortium: Grant Agreement No. 101000348. Unpublished report.*
- USDA-NRCS (2025). *Soil Texture Calculator*. Available online at: <https://www.nrcs.usda.gov/resources/education-and-teaching-materials/soil-texture-calculator> (Accessed September 4, 2025).
- Xu, L. K., and Hsiao, T. C. (2004). Predicted versus measured photosynthetic water-use efficiency of crop stands under dynamically changing field environments. *J. Exp. Bot.* 55, 2395–2411. doi: 10.1093/jxb/erh271
- Yazar, A., Gökçel, F., and Sezen, M. S. (2009). Corn yield response to partial rootzone drying and deficit irrigation strategies applied with drip system. *Plant Soil Environ.* 55, 494–503. doi: 10.17221/96/2009-PSE

- Yetik, A. K., and Sen, B. (2025). Optimizing lavender (*Lavandula angustifolia* Mill.) yield and water productivity with deficit irrigation in semi-arid climates. *Agronomy* 15:1009. doi: 10.3390/agronomy15051009
- Zhang, F., Chen, M., Xing, Y., and Wang, X. (2024). Appropriate nitrogen application under ridge–furrow plastic film mulching planting optimizes spring maize growth characteristics by improving soil quality in the Loess Plateau of China. *Agric. Water Manag.* 307:109259. doi: 10.1016/j.agwat.2024.109259
- Zhang, F., Wang, X., Liu, S., Ren, H., Wang, Y., Han, J., et al. (2025). Effects of different pipe burial depths on crop yield, water productivity, and irrigation water productivity: a global meta-analysis. *Eur. J. Agron.* 166:127562. doi: 10.1016/j.eja.2025.127562
- Zhen, S., and Burnett, S. E. (2015). Effects of substrate volumetric water content on English lavender morphology and photosynthesis. *HortScience* 50, 909–915. doi: 10.21273/HORTSCI.50.6.909