sustainability

MDPI

Article

A Self-Regulating, Low-Energy, Clay-Based Irrigation System: Performance Assessment in Moringa and Cowpea

Hunadi Chaba [1,2,*], Vjekoslav Tanaskovik [3,*], Hintsa Araya [1], Ordan Cukaliev [3], Nadia Araya [4], Martin Steyn [2], Mariette Truter [1], Althea Grundling [4], Sai Trinath Suryadevara [5], Jan Siering [6], Svetoslav Malchev [7], Stojanche Nechkovski [3], Tosho Arsov [3], Imaneh Goli [8] and Hossein Azadi [9]

[1] Agricultural Research Council-Vegetable, Industrial and Medicinal Plants (ARC-VIMP), Pretoria 0001, South Africa
[2] Department of Plant and Soil Sciences, University of Pretoria, Pretoria 0002, South Africa
[3] Faculty of Agricultural Sciences and Food, University of St. Cyril and Methodius in Skopje, 1000 Skopje, North Macedonia
[4] Agricultural Research Council-Natural Resources and Engineering (ARC-NRE), Pretoria 0001, South Africa
[5] Institute for Polymer and Production Technologies gGmbH, 23966 Wismar, Germany
[6] Robert Schmidt Institut, Hochschule Wismar University of Applied Sciences: Technology, Business and Design, 23966 Wismar, Germany
[7] Fruit Growing Institute—Plovdiv, Agricultural Academy, 4004 Plovdiv, Bulgaria
[8] Department of Economics and Rural Development, Gembloux Agro-Bio Tech, University of Liège, 5030 Gembloux, Belgium; imaneh.goli@uliege.be
[9] Department of Geography, Ghent University, 9000 Ghent, Belgium
* Correspondence: chabah@arc.agric.za (H.C.); vtanaskovic@fznh.ukim.edu.mk (V.T.)

Abstract

Crop failures are common in rain-fed farming in sub-Saharan Africa, especially in water-scarce South Africa. Inadequate rainfall necessitates innovative solutions to enhance food production. Water-saving irrigation technologies can significantly reduce crop failures, particularly for smallholder farms with limited access to irrigation water. This study evaluated the effects of Self-Regulating, Low-Energy, Clay-Based Irrigation System (SLECI), subsurface (SDI) and surface drip (DI) on the performance of moringa (*Moringa oleifera*) and cowpea (*Vigna unguiculata*), cultivated either as mono (sole) crops or in intercropping systems, in an open experimental field in South Africa. The experimental design was a factorial Randomized Complete Block Design (RCBD) replicated three times. The main aim was to assess water productivity and yield performance in different irrigation systems over two growing seasons. The results showed that the SLECI irrigation system was more suitable for *M. oleifera*, while *V. unguiculata* performed best with standard drip irrigation. Moringa oleifera fresh leaf biomass was higher under SLECI with sand around the clay element and surface drip irrigation with 1.42 t/ha, followed by the SLECI treatment without sand with 1.25 t/ha, while the least yield was noted in subsurface drip irrigation treatment with 1.18 t/ha. *Vigna unguiculata* (a dual-purpose crop for grain and leaves) produced higher total fresh biomass yield under subsurface drip irrigation treatment with 66.26 t/ha, followed by the SLECI treatment without sand (61.51 t/ha), while drip and SLECI with sand showed similar yield with 52.34 and 52.31 t/ha, respectively. In *M. oleifera*, the irrigation water productivity (IWP) varied from 0.26 kg/m^3 below the surface to 0.65 kg/m^3 after the SLECI treatment with sand. IWP in *V. unguiculata* treatments ranged from 27.52 kg/m^3 in SLECI without sand to 9.52 kg/m^3 under surface drip irrigation. In addition, chlorophyll content and stem diameter were elevated under SLECI, reflecting enhanced nutrient and water availability. The findings have important implications for sustainable agriculture under water-limited conditions.

Check for updates

Academic Editor: Jan Hopmans

Received: 19 December 2025
Revised: 3 February 2026
Accepted: 5 February 2026
Published: 11 February 2026

https://doi.org/10.3390/su18041853

Keywords: bio-based irrigation technologies; irrigation techniques; intercropping; sustainable agriculture

---

1. Introduction

One of the most pressing challenges for agricultural production in semiarid and arid regions is water scarcity [1,2]. The phenomena related to water scarcity are increasing freshwater consumption and the depletion of available freshwater supplies, leading to water stress. South Africa is among the driest countries, with evaporation exceeding rainfall by a factor of three due to high temperatures, limited precipitation, and an uneven rainfall distribution, with some regions receiving less than 100 mm per year. Efficient irrigation methods are required to achieve sustainable crop yields while preserving limited water resources [3–5]. Several studies have indicated that subsurface irrigation can enhance irrigation water productivity (IWP) by reducing evaporative losses and better targeting soil moisture in crop root zones [6,7].

Subsurface, Low-Energy Clay Irrigation represents an innovative climate-smart technology designed to optimize water use efficiency [1,8]. 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 [9,10]. Several studies have demonstrated the benefits of the SLECI irrigation technologies on diverse crops, including cucumber and mango [11], cherry orchards [8], pepper [12], lavender, rosemary, maize, gem squash, and tomato [13]. Additionally, in a study using wolfberries and apples, subsurface irrigation with ceramic emitters (SICE) performed better in terms of water use and crop output than drip irrigation and subsurface drip irrigation [14,15]. However, the responses vary depending on the type of soil and crop [16]. Sechube et al. [17] evaluated the economic cost of the SLECI system as a climate-smart agricultural innovation for smallholder farmers in South Africa.

Mahler [18] provided a thorough analysis of advances in clay-based irrigation technology used in agricultural production. This study evaluated the performance of SLECI compared with conventional surface and subsurface drip irrigation for two crops with contrasting root architectures and water requirements: Moringa (*M. oleifera*), a deep-rooted perennial tree harvested for vitamin-rich leaves, and cowpea (*V. unguiculata*), a short-season legume valued for its protein-dense pods. The study hypothesized that subsurface irrigation systems would increase crop yield, irrigation water productivity (IWP), and nutrient uptake while decreasing water consumption and evaporation. Therefore, the main objective was to evaluate the effects of SLECI on yield and crop performance, water use, and irrigation water productivity and to compare the results with those from conventional surface and subsurface irrigation systems and with relevant findings from the literature. Furthermore, this study aims to advance understanding of SLECI efficacy for smallholder farmers in semiarid Africa and in similar regions and conditions worldwide.

2. Materials and Methods

2.1. The Experimental Site and Research Design

Moringa (*Moringa oleifera*) and cowpea (*Vigna unguiculata*) crops were grown on open fields for two growing seasons (October 2022–September 2024) at the Agricultural Research Council Vegetable, Industrial and Medicinal Plants (ARC-VIMP) pilot site, which is located 36 km from Pretoria, South Africa. The pilot site is located at a latitude of 25°35′ S, a longitude of 28°21′ E, and 1165 m above sea level. The study was conducted in a 3×3 Factorial Randomized Complete Block Design (RCBD), replicated three times to ensure statistical headers. The layout consisted of three distinct blocks (replications) to account for field gradients. The field was divided into 27 individual plots (3 Cropping Systems × 3 Irrigation Systems × 3 Replications). Each block contained a complete set of nine treatment combinations.

The experimental site was 54 m × 40 m, giving a total area of 2160 m^2. For cowpea, the spacing was 0.3 m between intra-rows and 0.6 m between inter-rows. Moringa was planted at 2 m × 2 m between inter-row and intra-row spacing. Both moringa and cowpea were grown in a zigzag pattern (Figure 1).

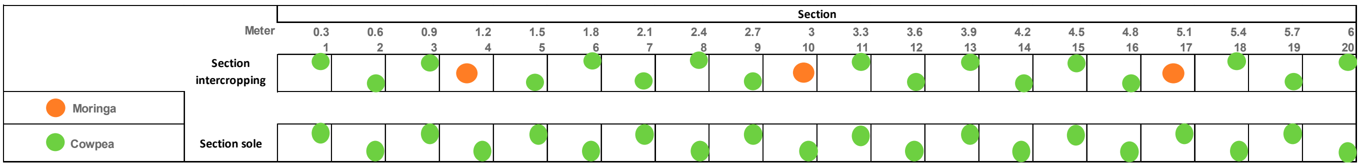


Figure 1. Experimental design: cowpea and moringa intercropped or sole-planted.

Standard drip irrigation, subsurface drip irrigation, SLECI irrigation with sand (SWS), and SLECI irrigation without sand (SWOS) were the treatments that were tested. The standard and subsurface irrigation systems used pressure-regulated drip tubes with an application rate of 2.3 L/h and emitters spaced at 30 cm. The SLECI emitter's application rate was 0.8–1.2 L/day at 1-bar of pressure, installed 30 cm below ground level (Figure 2). SLECI is an innovative and clay-based micro-irrigation system with significant potential to efficiently deliver water to plant roots, increasing crop yields while conserving water and energy. This subsurface irrigation system was developed by Prof. Dr. Harald Hansmann at the Institute for Polymer- and Produktionstechnologies (IPT) and was patented by Wismar University of Applied Sciences (HSW) in Germany (patent number: DE 102019005311.7). The system can meet crop water demands under all conditions without the need for external water management systems, irrigation plans, or soil moisture measurements. SLECI irrigation was automated based on atmospheric evaporative demand, whereas surface stand drip and subsurface drip irrigation were scheduled according to crop water requirements. Soil water content (m^3/m^3) was measured using a HOBO MX2307 Soil Moisture and Temperature Data Logger (Onset Computer Corporation, Bourne, MA, USA).

Figure 2. Subsurface Low-Energy Clay Irrigation line and installation of tubes.

The three middle rows per treatment were used for data collection. The data collected included, but was not limited to, plant height, leaf area, plant spread, fresh mass, and dry mass (Figure 3). The samples were then partitioned into leaves and stems.

Figure 3. Data collection on the novel ethnobotanical intercropping and SLECI field trial at ARC-VIMP.

The dry mass of the different plant parts was determined after oven drying to a constant mass at 65 °C. A ceptometer (AccuPAR model LP-80, Pullman, WA, USA) was used to measure the leaf area index (LAI) and fractional interception of photosynthetically active radiation (PAR). Using GenSTAT 10, data on water use, crop growth, yield, and physiological parameters were collected and subjected to ANOVA.

2.2. The Meteorological Conditions and Soil Characteristics

The experimental site is located in South Africa's summer rainfall (October–March) agro-climate zone, with a mean annual rainfall of 550 mm (Figure 4), but a notoriously erratic distribution. The average maximum temperature in January is 30 °C, while the average minimum temperature in July is 1.5 °C (Figure 4). The ideal temperature range for the tree is 25–35 °C [19]. However, research has shown that moringa is well-suited to temperatures between 20 and 40 °C and can withstand temperatures up to 48 °C during the summer months of May and June, which are common in the northwest region of India [20]. Additionally, it has been noted that the tree can withstand winter frost, has adapted to loose leaves, and remains dormant until optimal growth conditions appear in the spring [19]. Moringa is a drought-tolerant crop that can be grown with annual rainfall of 250–1500 mm [19] and under both rainfed and irrigated conditions [21]. According to Melo et al. [22], cowpeas are extremely tolerant to unfavorable weather conditions, including those seen in semiarid locations. Ramos et al. [23] state that although cowpea is well-suited to a variety of soil and climatic conditions, poor management may limit the crop's yield because it is susceptible to both excesses and shortages in water.

The long-term trend in our investigation indicates that average monthly reference evapotranspiration exceeds monthly precipitation, resulting in a water deficit that cannot meet the region's crop water requirements. However, the average monthly rainfall is much closer to the reference evapotranspiration in November and January, whereas it exceeds ETo in December. From February to July, precipitation gradually decreases, and from August to January, it gradually increases. Mabhaudhi et al. [24] reported that the region receives an average annual rainfall of 650 mm, with most occurring during the summer. Average daily air temperatures range from 8 to 34 °C in summer and from 4 to 23 °C in winter. Accordingly, January and July are the hottest and coldest months, respectively [25].

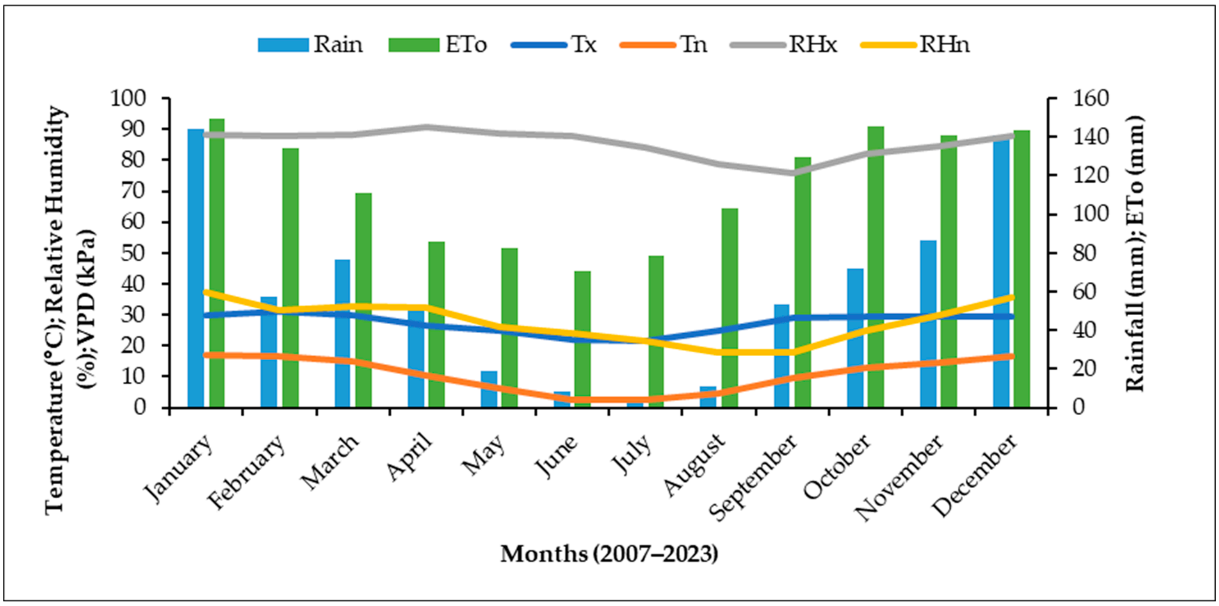


Figure 4. Long-term weather information of the study site for the period 2007–2023. Eto: Evapotranspiration; Tx = maximum temperature; Tn = minimum temperature; RHx = maximum relative humidity; RHn = Minimum relative humidity.

Moringa's root architecture includes a taproot that drills down to 2 m or more in light soils, enabling remarkable drought tolerance once the trunk thickens. On the other hand, EL-Sayed and Mahmoud [26] reported that higher yields of fresh moringa leaves can be achieved under intensive management and well-timed irrigation and fertigation. Cowpea belongs to the broader family of climate-smart legumes. Its prodigious nitrogen-fixing nodules enrich the soil while the pods reach marketable size within 80 to 90 days. The optimal temperature for cowpea plants ranges from 28 to 30 °C [27], but the plant tolerates heat above 35 °C and suffers flower abortion when topsoil moisture fluctuates wildly.

Key hydrologic, physical, and chemical characteristics of the soil at the pilot site are summarized in Table 1. In general, a large amount of sand is present in the soil at the experimental location. According to texture classification (soil texture triangle, USDA-NRCS), the soil at the pilot site is classified as sandy clay loam, with 66% sand, 26% clay, and 8% silt. Laboratory tests indicated field capacity at 24.4% and the permanent wilting point at 15.3% by volume [28,29]. With only 9% of the total available water, the soil's profile exposes plants to rapid drying if irrigation intervals are excessively prolonged. The moderate organic matter (2.1%) and near-neutral pH (7.2) suit both moringa and cowpea. The soil at the study site was highly saline, according to Duran's [30] electrical conductivity (EC) classification. Phosphorus content was moderate, whereas potassium availability was adequate. Both crops in our trial received a single broadcast of 100 k/ha of an 8-1-1 organic NPK blend.

Table 1. Chemical and physical properties of the 0–30 cm layer of the study site.

Chemical Characteristics	
pH in water	7.12
Electrical conductivity in dS/m	2.46–4.8
Organic matter in %	2.1%
Total N (Digestion and Colorimetric) in %	0.051
P (Bray-1) in mg/kg soil	13.2
K (Ammonium acetate) in mg/kg soil	22.5
Ca (Ammonium acetate) in mg/kg soil	1150.0
Mg (Ammonium acetate) in mg/kg soil	418.0

Table 1. *Cont.*

Particle Size	
Total sand in %	66.0
Silt in %	8.0
Clay in %	26.0
Physical Properties	
Permanent wilting point (soil moisture retention at 15 bars) in volume %	15.3
Field capacity (soil moisture retention at 0.33 bars) in volume %	24.4
Bulk density in g/cm^3	1.6

3. Results and Discussion

3.1. Effect of Irrigation on Moringa and Cowpea Yield

The results presented in Table 2 show that moringa's fresh leaf yield ranged from 1.18 t/ha under drip subsurface irrigation to 1.42 t/ha (DI and SLECI with sand), a difference of just 0.24 t/ha (around 17% of the mean). This yield was typical for a first-year moringa crop and was likely influenced by multiple factors (e.g., propagation material, climate, soil conditions, water availability, etc.). According to El-Sayed and Mahmoud [26], flood irrigation produced the highest moringa yields and yields of its constituent parts, compared with drip irrigation. In the same context, applying organic fertilizers improved moringa plant growth by increasing resistance to water stress, compared with chemical fertilization. In addition, when comparing the surface drip irrigation yield with that achieved in the SLECI plus sand treatment in our investigation, the yields are identical (1.42 t/ha). The comparison of SLECI with emitters covered by sand and SLECI with emitters not covered by sand showed a yield increase of 0.17 t/ha (≈12%) by removing the sand.

Table 2. Average fresh moringa leaves and cowpea total biomass yield (Ya) in t/ha and calculated Land Equivalent Ratio (LER) values.

Treatment	**Fresh Weight (t/ha)**		**Mean LER**
	Moringa	**Cowpea**	
DI	1.42 ^{a}	52.34 ^{b}	2.40 ^{d}
SDI	1.18 ^{a}	66.26 ^{a}	4.26 ^{c}
SWS	1.42 ^{a}	52.31 ^{b}	5.66 ^{b}
SWOS	1.25 ^{a}	61.51 ^{a}	6.59 ^{a}

Values in column followed by the same letter are not significantly different at a *p*-value greater than 0.05. LER = Land Equivalent Ratio.

According to Osei et al. [12], the SLECI system performs uniquely across various soil types with varying hydraulic characteristics, which can affect the amount of water available for plant absorption. Long-term data are still being collected, but preliminary research using SLECI in sweet cherry plantations indicates the potential to maintain yields with lower energy and water inputs than typical drip systems [8].

Furthermore, combined findings under various irrigation methods were obtained from the experimental research described in Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project [13]. Deep or permanent root systems readily adapt to self-regulated trickle feeding, as evidenced by SLECI yields that were comparable to or exceeded those of drip treatments across four of the six experimental locations, ranging from 78% in tomatoes to 7% in maize and nearly equal in gem squash. However, compared with SLECI irrigation, drip irrigation yielded higher yields of rosemary and lavender. According to another study, bell pepper treatment at a burial depth of 5 cm yielded the highest yield in the SLECI system [12].

Subsurface irrigation with ceramic emitters was found to significantly increase fruit yield, compared with subsurface or surface drip irrigation, in a study involving melon, wolfberry, and apple trees [14,15,31]. Bozkurt and Mansuroglu [32] found that during the spring growing cycle, varied drip tape insertion depths significantly affected green bean yields; the best yield was obtained at a buried depth of 10 cm.

Fresh cowpea's total biomass yields presented in Table 2 range from 52.31 to 66.26 t/ha, a spread of 13.95 t/ha or around 27% of the mean (58 t/ha). Cowpea performed best under subsurface drip irrigation, yielding 66.26 t/ha, followed by the SLECI treatment without sand, yielding 61.51 t/ha. In contrast, drip surface and SLECI with sand showed almost similar yields of 52.34 and 52.31 t/ha, respectively. The contrasting results for moringa and cowpea reflect their differing root systems and growth habits. SLECI's subsurface clay emitters are suitable for deep-rooted perennials, increasing water-use efficiency and reducing evaporative losses [8,9,16]. Cowpea, with shallow roots and early-season water requirements, requires surface or shallow subsurface drip irrigation to ensure seedling establishment and higher yields.

Furthermore, findings of other studies revealed that the SLECI systems installed at a depth of 30 cm initially had lower germination and plant emergence than drip irrigation. The Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project [13] states that soil in the SLECI systems should be watered before sowing or planting annual crops or by another method, until the plant forms a suitable root system. Oliveira et al. [33] found that daily irrigation was the most effective water regime for cowpea productivity, compared with 2, 3, and 4-day irrigation intervals in another study investigating drip irrigation frequencies.

Significant decreases in cowpea production and yield components under water-deficit conditions and under various irrigation water regimes have been reported [34,35]. Costa et al. [36] argue that reduced production under water-restricted conditions can be linked to soil moisture scarcity, which induces stomatal closure as a strategy to maintain cell turgor and prevent water loss through transpiration.

Moringa fresh leaf biomass was significantly higher when intercropped with cowpea under SLECI without sand (7.73 t/ha), followed by SLECI with sand (6.47 t/ha) over three harvests (Figure 5A). Legumes, such as cowpea, are known to fix biological nitrogen, which benefits the growth of intercropped plants. Similarly, moringa dry leaf biomass ranged from 1.30 to 1.55 t/ha under SLECI with sand and without sand, respectively, when intercropped with cowpea. On the other hand, cowpea performed best under standard drip irrigation, followed by subsurface drip irrigation, then SLECI with sand, and lastly SLECI without sand. This indicates that the SLECI irrigation system is better suited to tree crops than to annual crops such as cowpea. Generally, moringa performed better under SLECI than under standard drip irrigation or subsurface drip irrigation.

The Land Equivalent Ratio (LER) was calculated and analyzed (Table 2). The Land Equivalent Ratio is a measure of land-use efficiency in intercropping, compared to monoculture (sole cropping). To account for competition effects and evaluate the efficiency of the intercropping system, the Land Equivalent Ratio was calculated. The results demonstrated significant overyielding across all water management regimes, as indicated by total LER values consistently exceeding the unity threshold. The SWOS treatment achieved the highest system efficiency, with a total LER of approximately 6.59, primarily due to the substantial increase in moringa biomass relative to the sole-cropped counterpart. Conversely, while the DI system maintained a more balanced competitive relationship between species (LER approximately 2.40), treatments such as SWOS and SDI exhibited clear interspecific competition, with moringa's dominance resulting in a partial LER for cowpea of less than 1.04. These findings suggest that while intercropping significantly enhances total biomass production per unit area, the choice of irrigation system fundamentally alters the competitive balance and resource partitioning between the tree and legume components.

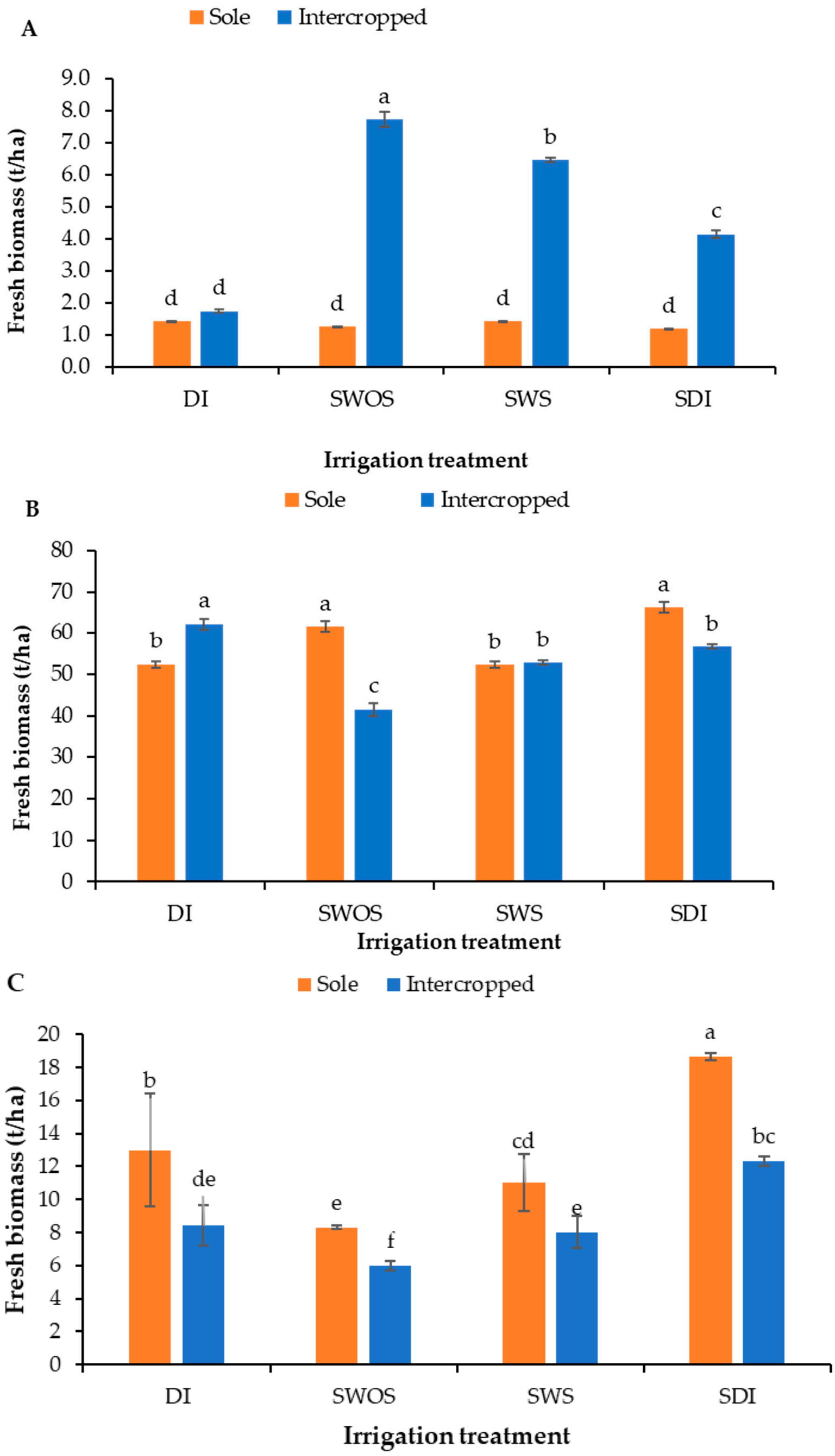


Figure 5. Fresh biomass of (**A**) moringa leaves, (**B**) cowpea (total), and (**C**) pods under different irrigation and cropping systems; Values in bar chart followed by the same letter are not significantly different at a *p*-value greater than 0.05.

3.2. Irrigation Water Use in Moringa and Cowpea Crops

Table 3 presents findings on irrigation water use at the experimental location during the vegetative season. Irrigation records in Table 3 indicate that the irrigation water delivered under the treatment was also affected by the irrigation techniques applied. The SLECI treatment with sand delivered only 2190 m^3/ha of water, while SLECI without sand delivered 2.1% more irrigation water per season for a total of 2235 m^3/ha. The surface drip irrigation treatment used almost 1.5 times as much irrigation water (5497 m^3/ha) per season as both SLECI treatments. Drip subsurface treatment showed approximately 30% higher irrigation water use than SLECI techniques, totaling 2842 m^3/ha for the season.

Table 3. Irrigation water applied (Iwa) per irrigation treatments (m^3/ha).

Treatment	Applied Irrigation Water Per Season (m^3/ha)
DI	5497 ^{c}
SDI	2842 ^{b}
SWS	2190 ^{a}
SWOS	2235 ^{a}

Values in column followed by the same letter are not significantly different at a *p*-value greater than 0.05.

The results corroborate those of Hansmann and Siering [11] and Malchev et al. [8], showing that SLECI is highly water-efficient and provides a comparatively low but steady water supply. According to the Technical Report on SLECI Pilot Sites Installed within the DIVAGRI Project [13], SLECI uses less irrigation water than drip irrigation for lavender, rosemary, maize, gem squash, and tomatoes. Additionally, drip irrigation used the most irrigation water for apple fruits and wolfberries [14], compared with alternative systems (subsurface irrigation with ceramic emitters or SICE) [15]. EL-Sayed and Mahmoud [26] reported irrigation water use ranging from 470 mm for drip irrigation to 630 mm for flood irrigation in their investigation of the moringa crop. Cowpea is a short-season summer crop that requires 250–360 mm of irrigation during the growing season. Krishna [37] stated that cowpeas need 360–450 mm of water each season for maximum productivity, whether it is fully irrigated, partially irrigated, or rainfed. Moringa and cowpea's seasonal water use under subsurface drip irrigation in our investigation is lower than that reported by EL-Sayed and Mahmoud [26] and Krishna [37]. In contrast, the results for drip surface irrigation showed higher use.

3.3. Soil Water Content

An essential tool for understanding soil moisture dynamics throughout the season and creating a suitable irrigation schedule is soil moisture monitoring and analysis [4]. Soil water content was measured using a HOBO MX2307 Soil Moisture (Volumetric Water Content, m^3/m^3) and Temperature (°C) Data Logger (Onset Computer Corporation, Bourne, MA, USA). Figure 6 presents soil water content over the first 60 days after planting; the damped oscillation in SLECI traces illustrates how gentle seepage stabilizes the soil moisture content. Furthermore, subsurface drip irrigation maintained stable water content throughout most of the recording period. In contrast, SLECI eliminates peaks and troughs by offering a slow, continuous delivery. According to Malchev et al. [8], fruit trees and other perennials with deep roots require this stability to reduce stress cycles and promote more consistent growth. Compared with surface drip irrigation and subsurface drip irrigation, SLECI continuously maintained a more consistent soil water content with less moisture fluctuations [13].

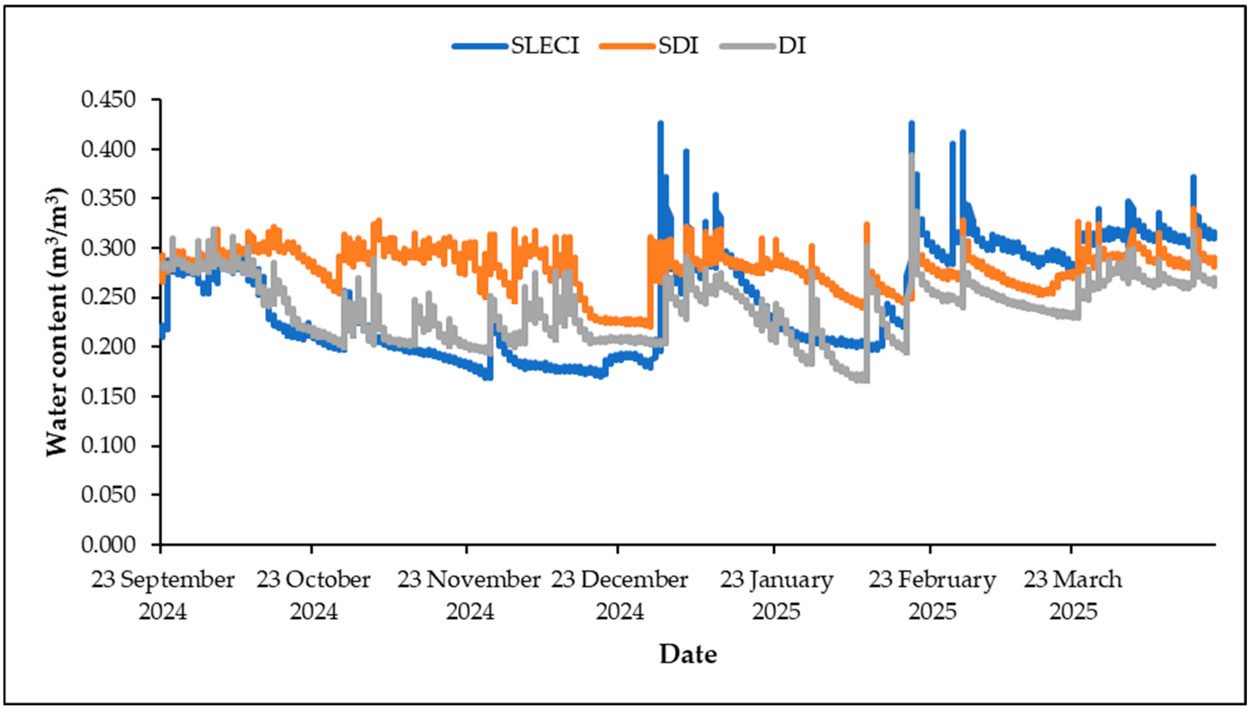


Figure 6. Soil water content (m^3/m^3) during the growing season.

According to the report's findings [13], in experiments with lavender and rosemary, the conventional drip irrigation treatment exhibited the greatest oscillation, followed by the subsurface drip irrigation treatment. In contrast, the SLECI treatment exhibits the least oscillation. Additionally, subsurface SLECI irrigation at 0–15 and 15–30 cm resulted in higher soil moisture content in maize crops, followed by surface drip and surface SLECI irrigation. In a study on apple trees, the difference in soil water levels between subsurface irrigation with ceramic emitters (SICE) and SDI was smaller than that for DI [15].

3.4. Irrigation Water Productivity in Moringa and Cowpea Under Different Irrigation Techniques

Irrigation water productivity, or IWP, is a widely used metric for evaluating irrigation schemes that use various water application quantities and procedures in agricultural output. It determines how many kilograms of commodities are produced per cubic meter of water. IWP, which reflects the degree of irrigation and agricultural technology management, is defined by Gang et al. [38] as the crop yield per unit of irrigation water consumption. The ratio of actual crop yield per unit of water used, expressed in kg/m^3, is known as irrigation water productivity in agriculture [39,40]. In addition to comparing irrigation techniques or procedures used in agricultural production, it is sometimes said to highlight maximizing crop yield under conditions of water scarcity [41]. Cetin et al. [42] found that irrigation water productivity research indicated that the quantity of water utilized in a farm and/or irrigation scheme is more significant to farmers and authorities. Lastly, IWP is crucial for sustaining agricultural output, especially in light of the anticipated climate change. Therefore, understanding the elements that affect IWP and developing measures to improve it are crucial scientific subjects. We estimated IWP in our analysis using the following equation:

$$IWP = \frac{Ya}{Iwa} \tag{1}$$

where Ya is crop fresh yield in kg/ha, IWP is irrigation water productivity in kg/m^3, and IWP is irrigation water applied in m^3/ha. The results for irrigation water productivity of moringa and cowpea are presented in Tables 4 and 5, respectively. Irrigation water productivity for moringa crops ranged from 0.26 kg/m^3 under the surface to 0.65 kg/m^3 when treated with sand for SLECI.

Table 4. Irrigation water productivity in moringa by different irrigation treatments (kg/m^3).

Treatment	Ya in kg	Iwa in m^3	IWP in kg/m^3	% from Surface Drip
DI	1420 ^{a}	5497 ^{c}	0.258 ^{c}	100.00
SDI	1180 ^{a}	2842 ^{b}	0.415 ^{b}	160.73
SWS	1420 ^{a}	2190 ^{a}	0.648 ^{a}	251.05
SWOS	1250 ^{a}	2235 ^{a}	0.559 ^{a}	216.51

Values in column followed by the same letter are not significantly different at a *p*-value greater than 0.05.

Table 5. Irrigation water productivity in cowpea by different irrigation treatments (kg/m^3).

Treatment	Fresh Weight in kg	Irrigation Water Use in m^3	IWP in kg/m^3	% from Surface Drip
DI	52,340 ^{b}	5497 ^{c}	9.52 ^{c}	100.00
SDI	66,260 ^{a}	2842 ^{b}	23.32 ^{b}	244.86
SWS	53,210 ^{b}	2190 ^{a}	24.30 ^{b}	255.18
SWOS	61,510 ^{a}	2235 ^{a}	27.52 ^{a}	289.04

Values in column followed by the same letter are not significantly different at a *p*-value greater than 0.05.

The highest water productivity was obtained in the SLECI treatment with sand (0.65 kg/m^3), which was more than two and a half times that of the surface drip irrigation treatment (0.26 kg/m^3). SLECI without sand reached 0.56 kg/m^3, which is more than twice that of DI. The results (Table 5) indicated that SLECI without sand produced almost three times better IWP in cowpea in comparison with the surface drip treatment or 27.52 vs. 9.52 kg/m^3, followed by SLECI with sand, with around two and a half times (23.13 kg/m^3) and subsurface drip irrigation treatment with 23.32 kg/m^3. Compared with the most efficient and widely used surface or subsurface drip irrigation technique, IWP results are similar to those reported for SLECI technology applied to rosemary, lavender, maize, tomato, and gem squash [13]. Furthermore, compared with subsurface drip-irrigated apples, subsurface irrigation with ceramic emitters at a depth of 40 cm resulted in considerably higher WUE and IWUE, by 14.8% and 6.5%, respectively [15].

The same system (SICE) demonstrated greater water-use efficiency in a separate wolfberry trial, outperforming drip irrigation by 14.6% and subsurface drip irrigation by 4.5%, respectively [14]. Compared with subsurface drip irrigation, SICE increased water production in melon crops by 13% [14]. Osei et al. [12] found that SLECI irrigation lines used less water when buried 10 cm deeper than at 5 or 10 cm in their investigation of bell pepper crops.

Additionally, our investigation's findings demonstrate that drip subsurface is more productive than surface drip, with over 60% of water consumed being productive. This is mainly because installing drip lines in the soil offers greater benefits than surface drip irrigation. In this context, El-Sayed and Mahmoud [26] reported higher field water use efficiency (FWUE) in moringa trees under drip irrigation than under flood irrigation. It can be stated that drip irrigation offers the advantages of uniform water distribution, reduced percolation, and less water applied during the growing season. According to Oliveira et al. [33], daily irrigation not only increased cowpea productivity compared to irrigation intervals of two, three, and four days, but also improved water use efficiency, making it a practical method for maximizing water application in semiarid areas where water availability is frequently scarce. According to Pimenta et al. [43], depending on the cowpea cultivars, WUE decreased from 0.24 to 0.49 kg/m^3 for every 1% increase in water application.

Generally, our investigation showed that the SLECI system produces the same fresh yield with half to about one and a half times less water in the moringa crop, or with about one and a half to two times less water use in the cowpea crop. Therefore, when the goal is maximum biomass per liter rather than absolute tonnage, SLECI offers the most significant advantage. Growers under irrigation would double or even triple economic returns per cubic meter by adopting the SLECI treatment, with or without sand.

3.5. The Effect of Irrigation Techniques on Plant Height, Leaf Area Index, Chlorophyll Content, and Stem Diameter

The effect of irrigation techniques on moringa and cowpea is presented in Figure 7. According to the results, different irrigation systems had no significant effect on moringa height (Figure 7A). However, significant differences were recorded on sole cowpeas with taller plants under a subsurface irrigation system (Figure 7B). In other research on irrigation systems for the moringa tree, El-Sayed and Mahmoud [26] reported higher plant height under drip irrigation (136 and 160 cm) than under flood irrigation (84 and 91 cm in the 1st and 2nd cut back, respectively).

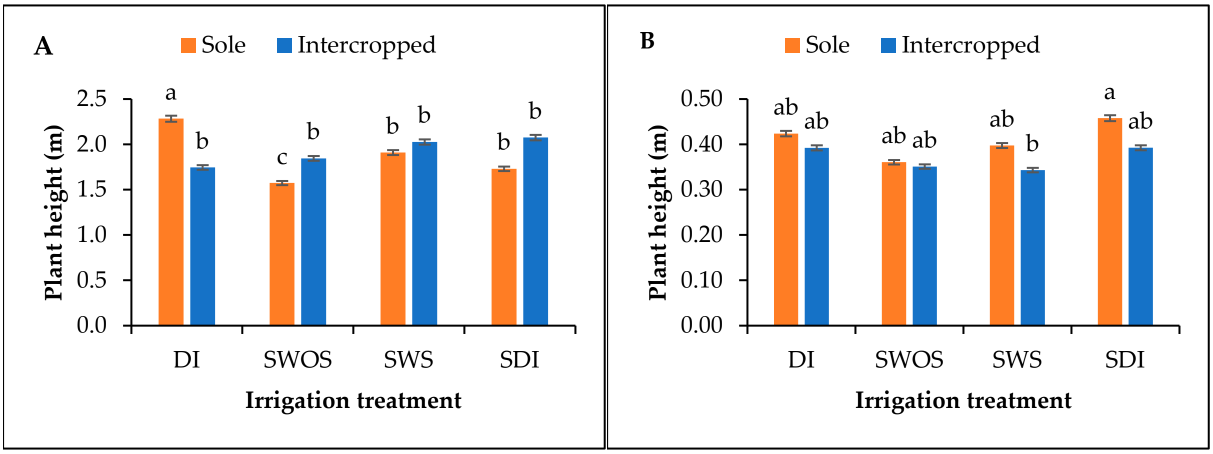


Figure 7. Plant height response in moringa (**A**) and cowpea (**B**) to different irrigation systems. DI = surface drip irrigation. SDI = subsurface drip irrigation; SWS = SLECI with sand and SWOS = SLECI without sand; Values in bar chart followed by the same letter are not significantly different at a *p*-value greater than 0.05.

The leaf area index (LAI) of cowpea and moringa was measured using a ceptometer (AccuPAR model LP-80, Pullman, WA, USA). The LAI of moringa was higher when it was intercropped with cowpea under a standard drip irrigation system (Figure 8A). The other treatments, however, were not significantly different. Similarly, cowpea LAI was higher under a standard drip irrigation system, whether in sole cropping or intercropping (Figure 8B). However, other irrigation treatments had no significant effect on cowpea LAI (Figure 8B). A study of tomato and cucumber plants under full irrigation showed higher LAI and canopy cover than those under deficit irrigation [44]. An expanded canopy enables greater light interception and carbon assimilation, thereby enhancing biomass accumulation. A plant's ability to photosynthesize is directly correlated with the leaf area index, which is the percentage of total leaf area to ground area [45]. Well-irrigated plants typically exhibit a higher LAI due to increased leaf expansion and delayed senescence. Conversely, drought stress reduces LAI by causing leaf rolling, abscission, or stunted leaf growth [46].

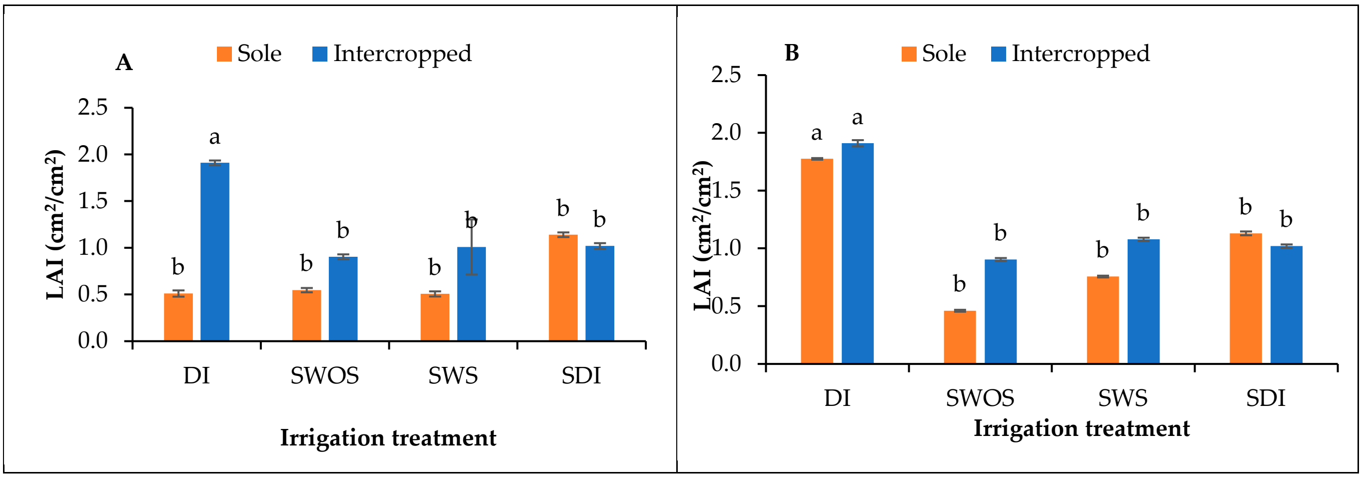


Figure 8. Leaf area index (LAI) of moringa (**A**) and cowpea (**B**) under different irrigation systems; Values in bar chart followed by the same letter are not significantly different at a *p*-value greater than 0.05.

The chlorophyll content of moringa and cowpea was measured using a SPAD-502Plus (units) (Konica Minolta, Tokyo, Japan) chlorophyll meter. The collected data indicated that the chlorophyll content of both moringa and cowpea was higher during the active growth stage (22-Mar-23) than during the early and late growth stages (Figure 9). Chlorophyll content reflects the photosynthetic efficiency and health of plants. A comprehensive review showed that chlorophyll biosynthesis and photosystem performance are strongly affected by multiple abiotic stresses. The chlorophyll content is tightly linked to photosynthetic efficiency because stresses (such as drought or nutrient deficiency) reduce pigment synthesis and damage photosynthetic machinery [47]. Water deficit induces chlorophyll degradation through oxidative stress, limiting light capture and reducing photosynthetic rates.

The SLECI irrigation system, with or without sand, generally resulted in higher chlorophyll content in both crops. This could be related to the irrigation system's potential to reduce leaching of mobile mineral nutrients, such as nitrogen (N), since nitrogen is known to improve crop chlorophyll content. In this context, El-Sayed and Mahmoud [26] reported that moringa plants under drip irrigation had higher chlorophyll levels than those under flood irrigation. Furthermore, fertilizers (compost/organic fertilizer and rock phosphate) tended to increase total chlorophyll a and b content, as reported by the same authors.

The stem diameter (mm) of moringa was measured using a Digital Vernier Calliper (Mitutoyo 500-737-20CAL, Mitutoyo Corporation, Kawasaki, Japan) at ≈ 10 cm above ground. The data indicated that moringa intercropped with cowpea under SLECI without sand had thicker stems than the other treatments (Figure 10). The increase in stem thickness under the SLECI irrigation system may support enhanced biomass growth. However, moringa trees under standard drip irrigation had thinner stems than those under other treatments. Stem diameter indicates a plant's structural strength and assimilate allocation. In another study with tomato crop, the SLECI irrigation treatment produced thicker stems in comparison with conventional surface drip irrigation [48]. Under water stress, reduced turgor and assimilate supply resulted in thinner stems, lower mechanical strength, and decreased hydraulic conductance. El-Sayed and Mahmoud [26] reported that drip irrigation treatments yielded higher stem diameter values than flood irrigation treatments.

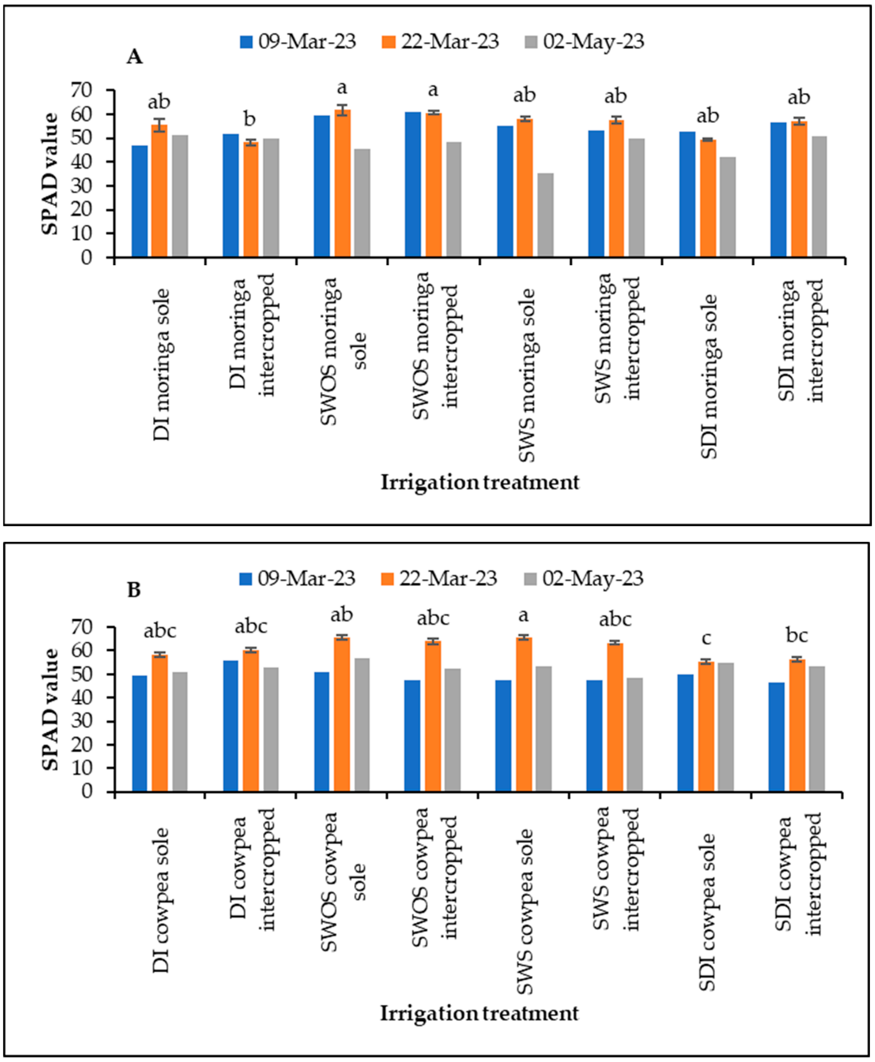


Figure 9. Chlorophyll content response of moringa (**A**) and cowpea (**B**) to different irrigation systems. The SPAD values were significant (p-value = 0.0006) on 22 March 23; Values in bar chart followed by the same letter are not significantly different at a p-value greater than 0.05.

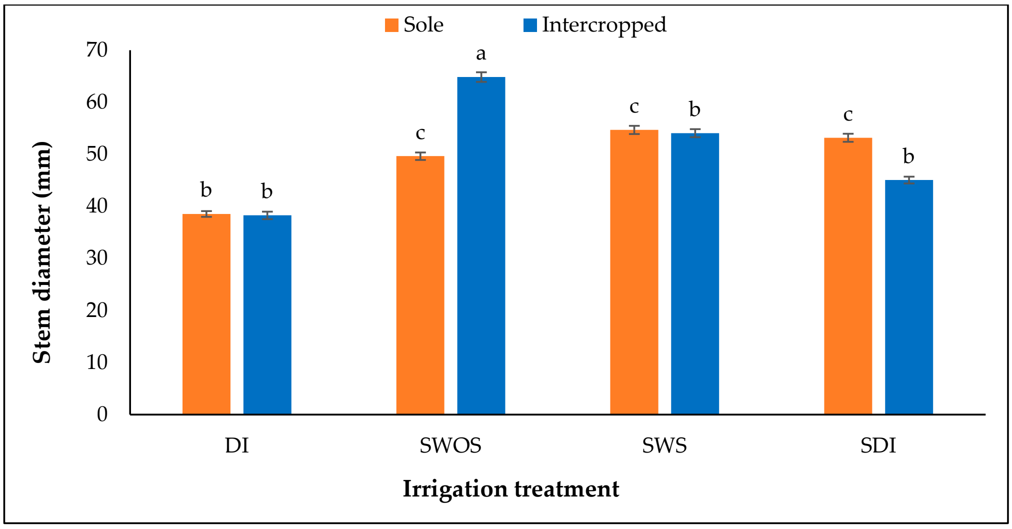


Figure 10. Stem diameter of moringa in response to different irrigation systems; Values in bar chart followed by the same letter are not significantly different at a p-value greater than 0.05.

3.6. The Effect of Irrigation Techniques on the Nutritional Quality of Moringa Leaves and Cowpea Seeds

Global demand for nutritious food is rising alongside population growth, while climate-driven water scarcity, droughts, and environmental degradation simultaneously reduce agricultural productivity. Irrigation, which is the artificial application of water to crops, has traditionally aimed to maximize yield. However, recent research indicates that irrigation strategies significantly influence the nutrient composition and the production of bioactive compounds in plants. Plants require enough water for photosynthesis, nutrient transport, and metabolic processes. Water shortages or excesses can disrupt these functions, leading to issues with nutrient uptake, enzyme activity, and the production of secondary metabolites such as phenolics and carotenoids [49,50]. As a result, irrigation techniques significantly impact both biomass and nutritional value.

SLECI with sand tended to increase total sugars and total non-structural carbohydrates (TNC %) in cowpea (e.g., up to 11.62%). In comparison, subsurface drip irrigation maintained more stable protein levels (≈24–26%) and energy stability (≈1395–1419 kJ/100 g) in both crops (Tables 6 and 7). SLECI without sand also increased fat content (≈3.5–4.2%) and slightly higher energy levels, possibly due to better aeration and nutrient delivery. Traditional drip irrigation preferred a protein–carbohydrate balance with lower variability among samples, resulting in better field control of moisture and nutrient application. Sand addition to SLECI reduced ash by a small margin but increased total sugars and starch, indicating enhanced carbohydrate translocation under moderate substrate aeration. On the other hand, SLECI without sand enhanced protein and fat retention, perhaps due to improved retention of the soil nutrient solution.

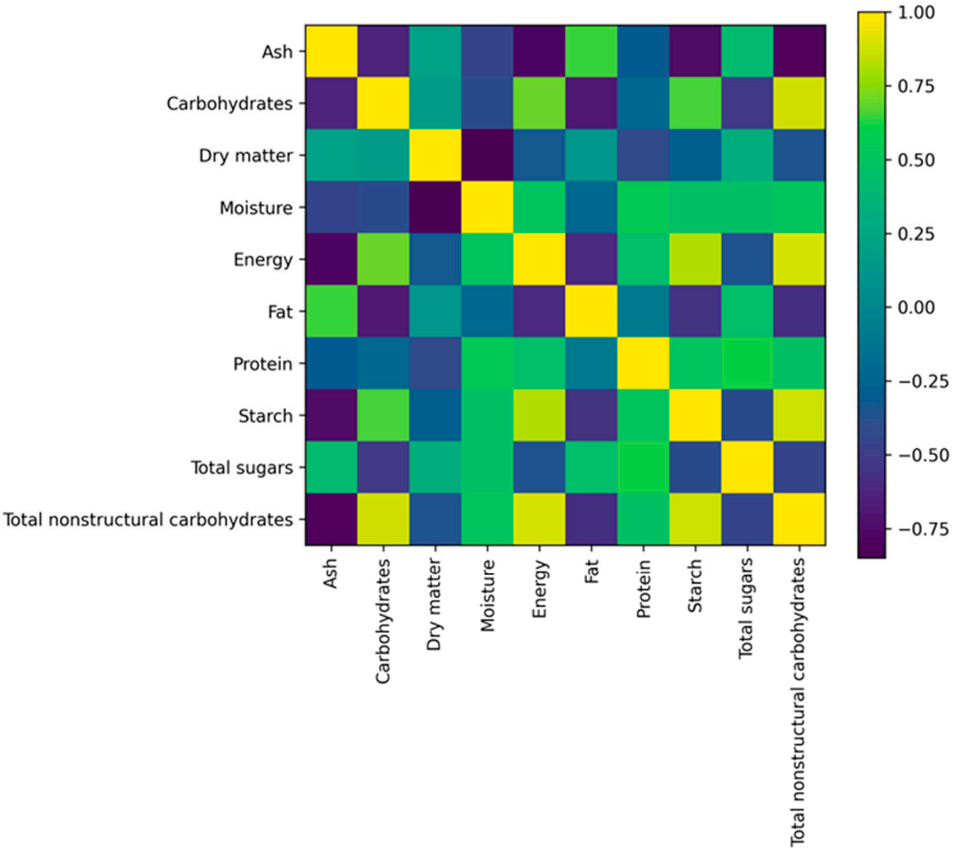
Table 6. Cowpea nutritional quality as influenced by different irrigation treatments.

Treatment	Ash (%)	Carbohydrates Calculated (%)	Dry Matter (%)	Moisture (%)	Energy Calculated (kJ/100 g)	Fat (%)	Protein (%)	Starch (%)	Total Sugars (%)	Total Non-Structural Carbohydrates (%)
DI	8.3	55.5	91.8	8.2	1443.5	1.2	25.0	16.7	7.3	24.1
SDI	8.3	58.5	91.5	8.5	1442.8	1.4	23.2	15.4	8.7	24.1
SWS	8.1	60.9	91.7	8.3	1454.5	1.7	21.0	17.2	9.6	26.9
SWOS	8.2	60.0	91.7	8.3	1456.0	1.8	21.8	17.7	7.2	24.9

Table 7. Moringa leaf nutritional quality as influenced by different irrigation treatments.

Treatment	Ash (%)	Carbohydrates Calculated (%)	Dry Matter (%)	Moisture (%)	Energy Calculated (kJ/100 g)	Fat (%)	Protein (%)	Total Sugars (%)	Total Non-Structural Carbohydrates (%)
DI	12.4	51.3	91.4	8.6	1414.0	3.6	24.2	15.2	15.3
SDI	12.5	49.9	91.3	8.7	1411.0	3.6	25.3	13.9	13.9
SWS	12.3	51.5	91.8	8.2	1417.0	3.3	24.6	13.9	13.9
SWOS	13.4	50.2	91.4	8.6	1407.0	4.0	23.8	12.3	12.3

Pearson correlation analysis (Figure 11) identified clear correlations among the measured nutritional parameters, reflecting the biochemistry and physiology of the interactions that underlie nutrient forms in foods and plant tissues. Energy content, as expected, correlated strongly and positively with proteins and carbohydrates, as these are largely responsible for the calorie content in plant tissue [51,52]. Carbohydrates provide the bulk of metabolizable energy via glycolytic and oxidative pathways, with proteins serving as a caloric source after deamination and oxidation [53]. These samples are rich in carbohydrates, protein, and energy, a characteristic often observed in legumes, cereals, and leafy vegetables [54,55]. Conversely, there was a negative correlation between energy content and moisture, as moisture primarily dilutes energy content. In other words, increased water content reduces the relative dry matter concentration and, accordingly, caloric density [51,56]. Higher-nutrient samples with more moisture contain less dry matter per unit weight and therefore lower the net yield of energy when oxidized metabolically or burned [57]. For example, freshly picked leafy greens have a high water content (>85%) and thus have a lower energy density than dehydrated or starchy plant foods such as legumes or grains [58].



Relationship	r	R²	Interpretation
Energy vs. Carbohydrates	0.88	0.77	77% of variation in energy is explained by Carbohydrates
Energy vs. Protein	0.79	0.62	Strong positive relationship
Energy vs. Moisture	−0.82	0.67	Strong negative, strong dilution effect
Fat vs. Energy	0.67	0.45	Moderate positive association
Protein vs. Ash	0.54	0.29	Weak–moderate positive association
Dry matter vs. Moisture	−0.85	0.72	Very strong inverse relationship

Figure 11. Pearson correlations heat map of nutritional components.

There are strong positive correlations between protein and ash content, suggesting that increased protein content is associated with increased mineral content, since some important minerals (e.g., Fe, Zn, Mg, and K) coexist with protein molecules, such as enzymes and structural proteins [55,59]. Similarly, fat content is directly related to energy and negatively or weakly related to moisture, since lipids are hydrophobic, high-energy molecules that accumulate in drier plant material [60]. Furthermore, carbohydrates inversely correlate with crude fiber in legumes and leafy vegetables. This is because structural carbohydrates (hemicellulose, cellulose, and lignin) increase with plant maturity, typically at the expense of soluble carbohydrates such as starches and sugars [61]. On the contrary, those with higher fiber content have lower digestible carbohydrate and energy values.

Protein–fat relationships vary according to crop and environmental conditions. Oilseeds such as groundnut, soybean, and moringa often exhibit positive correlations between fat and protein, as both are deposited in the seeds during maturation [60,62]. Leafy vegetables generally exhibit low or negative correlations between fat and protein because nitrogenous and lipid compounds are distributed differently within leafy tissues [63,64]. Overall, the nutrient correlation pattern indicates the interrelatedness of plant biochemical composition, such that increases in one component could influence others through common biosynthetic pathways or compositional demands. Such correlation studies are significant for nutritional characterization, food product design, and breeding programs aimed at improving energy and nutrient content [51,56,59].

4. Conclusions

This study demonstrated that SLECI can substantially reduce irrigation water use (>60%) while maintaining or increasing crop yields, particularly for perennial crops such as moringa. This was prevalent when moringa was intercropped with cowpea under SWOS and SWS irrigation treatments. Cowpea, in contrast, performed better under subsurface drip irrigation due to its shallow root system; therefore, SLECI was installed at a depth of 30 cm. However, SLECI significantly improved irrigation water productivity for both crops, achieving 2- to 3-fold improvements over surface drip irrigation, making it an ideal irrigation system in water-scarce areas such as semiarid regions. Similarly, physiological parameters such as chlorophyll content and stem diameter were enhanced under SLECI, consistent with improved nutrient and water availability, which optimize the retention of simple carbohydrates (sugars), which are most ideal for flavor- and energy-dense foods. Future research should explore optimized emitter depths for annual crops, evaluate long-term impacts on soil salinity, and test the system across different soil types and climates.

Author Contributions: Conceptualization, methodology, formal analysis, investigation, resources, data curation, writing—original draft preparation, H.C., V.T., and H.A. (Hintsa Araya); review and editing, supervision, M.S., V.T., H.A. (Hintsa Araya), and H.A. (Hossein Azadi); conceptualization, writing—review, and editing, O.C., J.S., A.G. and S.M.; writing—review and editing, N.A., M.T., A.G., S.T.S., S.N., T.A., and I.G.; validation and project administration, H.A. (Hossein Azadi) and V.T. All authors have read and agreed to the published version of the manuscript.

Funding: The study received funds from the European Union Horizon 2020 programme under grant No. 101000348.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

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

References

1. Pereira, D.; Leitao, J.C.C.; Gaspar, P.D.; Fael, C.; Falorca, I.; Khairy, W.; Wahid, N.; El Yousfi, H.; Bouazzama, B.; Siering, J.; et al. Exploring Irrigation and Water Supply Technologies for Smallholder Farmers in the Mediterranean Region. *Sustainability* **2023**, *15*, 6875. [CrossRef]
2. Yazar, A.; Gökçel, F.; Sezen, M.S. Corn yield response to partial rootzone drying and deficit irrigation strategies applied with drip system. *Plant Soil Environ.* **2009**, *55*, 494–503. [CrossRef]
3. Moteva, M.; Spalevic, V.; Gigova, A.; Tanaskovik, V. Water Use Efficiency and Yield-Dependences for Canola (*Brassica napus*, L.) under Irrigation. *Agric. For.* **2016**, *62*, 403–413. [CrossRef]
4. Tanaskovik, V.; Cukaliev, O.; Kanwar, S.R.; Heng, L.K.; Markoski, M.; Spalevic, V. Nitrogen Fertilizer Use Efficiency of Pepper as Affected by Irrigation and Fertilization Regime. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2016**, *44*, 525–532. [CrossRef]

5. Mancosu, N.; Snyder, R.L.; Kyriakakis, G.; Spano, D. Water Scarcity and Future Challenges for Food Production. *Water* **2015**, *7*, 975–992. [CrossRef]
6. Yang, T.; Cherchian, S.; Liu, X.; Shahrokhnia, H.; Mo, M.; Šimůnek, J.; Wu, L. Effect of Water Application Methods on Salinity Leaching Efficiency in Different Textured Soils Based on Laboratory Measurements and Model Simulations. *Agric. Water Manag.* **2023**, *291*, 107734. [CrossRef]
7. Yang, M.-D.; Leghari, S.J.; Guan, X.-K.; Ma, S.-C.; Ding, C.-M.; Mei, F.-J.; Wei, L.; Wang, T.-C. Deficit subsurface drip irrigation improves water use efficiency and stabilizes yield by enhancing subsoil water extraction in winter wheat. *Front. Plant Sci.* **2020**, *11*, 508. [CrossRef]
8. Malchev, S.; Kornov, G.; Hansmann, H. 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.* **2022**, *76*, 45–55. [CrossRef]
9. Agbesi, W.E.K.; Sam-Amoah, L.K.; Darko, R.O.; Kumi, F.; Boafo, G. 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* **2025**, *17*, 2058. [CrossRef]
10. Elmajetni, I.; Wahid, N.; Taoufiki, N.; Sabri, A.; Krause, R.; Siering, J.; Bouazzama, B. Hydraulic characterization of Moistube and SLECI irrigation systems compared to conventional drip irrigation. *Agric. Eng. Int. CIGR J.* **2025**, *27*, 42–51.
11. Hansmann, H.; Siering, J. 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 the Sahel Zone Using Ghana as an Example]. German Research Report on Agricultural Innovations. 2018. Available online: https://edocs.tib.eu/files/e01fn20/1690620927.pdf (accessed on 15 August 2025).
12. Osei, G.; Sam-Amoah, L.K.; Owusu-Sekyere, J.; Hansmann, H.; Kumi, F.; Menash, K. Performance characteristics of self-regulating low energy clay-based irrigation system in different soil types. *J. Ghana Inst. Eng.* **2025**, *25*, 9–15. [CrossRef]
13. University of Ss. Cyril and Methodius in Skopje. *Technical Report on SLECI Pilot Sites Installed Within the DIVAGRI Project*; Partner 21: Skopje, North Macedonia, 2025.
14. Han, M.; Zhang, L.; Liu, X. Subsurface irrigation with ceramic emitters improves wolfberry yield and economic benefits on the Tibetan Plateau, China. *J. Arid Land* **2023**, *15*, 1376–1390. [CrossRef]
15. Cai, Y.; Wu, P.; Zhu, D.; Zhang, L.; Zhao, X.; Gao, X.; Ge, M.; Song, X.; Wu, Y.; Dai, Z. 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.* **2021**, *313*, 107404. [CrossRef]
16. Guo, J.; Zheng, L.; Ma, J.; Li, X.; Chen, R. Meta-analysis of the effect of subsurface irrigation on crop yield and water productivity. *Sustainability* **2023**, *15*, 15716. [CrossRef]
17. Sechube, M.; Chaba, H.; du Plooy, C.; Truter, M.; Araya, H.T. Evaluating the economic cost of the self-regulating, low-energy, clay-based irrigation system as a climate-smart agricultural innovation for smallholder farmers, South Africa. In *Climate-Smart Agriculture: Evidence-Based Case Studies in South Africa*; Agricultural Research Council (ARC)—Natural Resources and Engineering (ARC-NRE): Pretoria, South Africa, 2023; pp. 209–213.
18. Mahler, E. Innovations in Clay-Based Irrigation Technologies—A Systematic Review. *Sustainability* **2024**, *16*, 7029. [CrossRef]
19. Price, M.L. *The Moringa Tree*; Echo Technical Notes; ECHO: North Ft. Myers, FL, USA, 2000. Available online: https://allaboutmoringa.info/wp-content/uploads/2020/11/Ebook-The-Moringa-Tree-echo.pdf (accessed on 7 September 2025).
20. Pandey, A.; Pradheep, K.; Gupta, R.; Nayar, E.R.; Bhandari, D.C. 'Drumstick tree' (*Moringa oleifera* Lam.): A multipurpose potential species in India. *Genet. Resour. Crop Evol.* **2011**, *58*, 453–460. [CrossRef]
21. Dalal, N.R.; Bhalekar, M.N.; Ranpise, S.A.; Dalal, S.R. Irrigation water management on growth, flowering and yield of drumstick (*Moringa oleifera* Lamk.) cv. Bhagya. *J. Pharmacogn. Phytochem.* **2021**, *10*, 749–752.
22. Melo, A.S.D.; Melo, Y.L.; Lacerda, C.F.D.; Viégas, P.R.; Ferraz, R.L.D.S.; Gheyi, H.R. Water restriction in cowpea plants [*Vigna unguiculata* (L.) Walp.]: Metabolic changes and tolerance induction. *Rev. Bras. Eng. Agric. Ambient.* **2022**, *26*, 190–197. [CrossRef]
23. Ramos, H.M.M.; Bastos, E.A.; Cardoso, M.J.; Ribeiro, V.Q.; Nascimento, F.N. Produtividade degrãos verdes do feijão-caupi sob diferentes regimes hídricos. *Eng. Agric.* **2014**, *34*, 683–694. [CrossRef]
24. Mabhaudhi, T.; Modi, A.T.; Beletse, Y.G. Parameterisation and evaluation of the FAO-AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace. *Agric. For. Meteorol.* **2014**, *192–193*, 132–139. [CrossRef]
25. Mokgehle, S.; Araya, N.; Mofokeng, M.; Makgato, M.; Amoo, S.; Maboka, K.; du Plooy, C.; Araya, H. Regrowth response and nutritional composition of *Moringa oleifera* to cutting back in three agro-ecological zones in South Africa. *Horticulturae* **2022**, *8*, 963. [CrossRef]
26. El-Sayed, M.M.; Mahmoud, A.W.M. Irrigation and fertilization practices for *Moringa* plant growth under Upper Egypt conditions. *Middle East J. Appl. Sci.* **2018**, *8*, 145–156.
27. Dugje, I.Y.; Omoigui, L.O.; Ekeleme, F.; Kamara, A.Y.; Ajeigbe, H. *Farmers' Guide to Cowpea Production in West Africa*; IITA: Ibadan, Nigeria, 2009.

28. Evett, S. Soil Water and Monitoring Technology. In *Irrigation of Agricultural Crops*, 2nd ed.; Agronomy Monograph No. 30; Lascano, R.J., Sojka, R.E., Eds.; American Society of Agronomy: Madison, WI, USA, 2007; 664p.
29. Ryan, J.; Estefan, G.; Rashid, A. *Soil and Plant Analysis Laboratory Manual*, 2nd ed.; ICARDA: Beirut, Lebanon, 2001.
30. Durand, J.H. *Les Sols Irrigables; Etude Pedologique*; Presses Universitaires de France: Paris, France, 1983.
31. Han, M.; Zhang, L.; Zhao, X.; Xie, K. Subsurface Irrigation with Ceramic Emitters Improved the Water Productivity and Nitrogen Use Efficiency of Greenhouse Melons. *Irrig. Drain.* **2025**, *74*, 885–899. [CrossRef]
32. Bozkurt, S.; Mansuroglu, G.S. Responses of unheated greenhouse grown green bean to buried drip tape placement depth and watering levels. *Agric. Water Manag.* **2018**, *197*, 1–8. [CrossRef]
33. Oliveira, C.E.D.; Nascimento, A.A.D.; Moura, J.M.D.; Silva, M.L.; Fernandes, C.N.; Silva, A.R.D. Effects of water regimes and irrigation frequencies on cowpea growth. *Eng. Agric.* **2025**, *45*, e20240181. [CrossRef]
34. Ezin, V.; Tosse, A.G.C.; Chabi, I.B.; Ahanchede, A. Adaptation of cowpea (*Vigna unguiculata* (L.) Walp.) to water deficit during vegetative and reproductive phases using physiological and agronomic characters. *Int. J. Agron.* **2021**, *2021*, 9665312. [CrossRef]
35. de Pinho Sousa, D.; Nunes, H.G.G.C.; Ferreira, D.P.; Moura, V.B.; de Aviz, W.L.C.; Santos, H.C.A.; de Novoa Pinto, J.V.; de Oliveira Vieira, I.C.; Fernandes, G.S.T.; Silva, E.R.R.; et al. Performance of Cowpea under Different Water Regimes in Amazonian Conditions. *Horticulturae* **2022**, *8*, 335. [CrossRef]
36. Costa, D.L.P.; Takaki, A.Y.; da Silva Farias, V.D.; de Oliveira Teixeira, E.; Nunes, H.G.G.C.; de Oliveira Ponte de Souza, P.J. Stomatal conductance of cowpea submitted to different hydric regimes in Castanhal, Pará, Brazil. *J. Agric. Stud.* **2020**, *8*, 138–149. [CrossRef]
37. Krishna, K.R. *Agroecosystems of South India: Nutrient Dynamics, Ecology and Productivity*; BrownWalker Press: Boca Raton, FL, USA, 2010; 521p.
38. Gang, L.; Chenglong, Z.; Huo, Z.; Li, Y. Achieving comprehensive water productivity improvement: A multi-objective simulation-optimization model for water productivity-oriented irrigation water management. *Agric. Water Manag.* **2025**, *309*, 109316. [CrossRef]
39. Çetin, Ö.; Kara, A. Assesment of water productivity using different drip irrigation systems for cotton. *Agric. Water Manag.* **2019**, *223*, 105693. [CrossRef]
40. Fernández, J.E.; Alcon, F.; Diaz-Espejo, A.; Hernandez-Santana, V.; Cuevas, M.V. 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.* **2020**, *237*, 106074. [CrossRef]
41. Ali, M.H.; Talukder, M.S.U. Increasing water productivity in crop production—A synthesis. *Agric. Water Manag.* **2008**, *95*, 1201–1213. [CrossRef]
42. Çetin, Ö.; Doganay, K.H.; Tari, A.F. Assessment of water and economic productivity in irrigation management. In Proceedings of the XII International Scientific Agricultural Symposium "Agrosym 2021", Jahorina, Bosnia and Herzegovina, 7–10 October 2021; pp. 968–974.
43. Pimenta, L.J.L.; dos Santos, S.R.; Bernardino, D.L.M.P.; Barbosa, J.A.E.; Alves, A.G.T.; de Carvalho, A.J. Produtividade e eficiência do uso da água de cultivares do feijão-caupi sob irrigação por gotejamento. *Contrib. Cienc. Soc.* **2023**, *16*, 26504–26522. [CrossRef]
44. Mamun Hossain, S.A.A.; Lixue, W.; Chen, T.; Li, Z. Leaf area index assessment for tomato and cucumber growing period under different water treatments. *Plant Soil Environ.* **2017**, *63*, 461–467. [CrossRef]
45. Sarkar, S.; Cazenave, A.B.; Oakes, J.; McCall, D.; Thomason, W.; Abbott, L.; Balota, M. Aerial high-throughput phenotyping of peanut leaf area index and lateral growth. *Sci. Rep.* **2021**, *11*, 21661. [CrossRef]
46. Zhang, Y.J.; Xie, Z.K.; Wang, Y.J.; Su, P.X.; An, L.P.; Gao, H. Effect of water stress on leaf photosynthesis, chlorophyll content, and growth of oriental lily. *Russ. J. Plant Physiol.* **2011**, *58*, 844–850. [CrossRef]
47. Sharma, A.; Kumar, V.; Shahzad, B.; Ramakrishnan, M.; Sidhu, G.P.S.; Bali, A.S.; Handa, N.; Kapoor, D.; Yadav, P.; Khanna, K.; et al. Photosynthetic Response of Plants Under Different Abiotic Stresses: A Review. *J. Plant Growth Regul.* **2020**, *39*, 509–531. [CrossRef]
48. Cukaliev, O.; Kumi, F.; Tanaskovik, V.; Agbesi, W.E.K.; Trinath Suryadevara, S.; Malchev, S.; Siering, J.; Azadi, H.; Nechkovski, S.; Bogevska, Z.; et al. Field evaluation of tomato crop production under SLECI irrigation. *Agric. For.* **2025**, *71*, 145–161. [CrossRef]
49. Mahajan, M.; Singh, A.; Singh, R.P.; Gupta, P.K.; Kothari, R.; Srivastava, V. Understanding the benefits and implications of irrigation water and fertilizer use on plant health. *Environ. Dev. Sustain.* **2024**, *26*, 20561–20582. [CrossRef]
50. Wadood, A.; Hameed, A.; Akram, S.; Ghaffar, M. Unraveling the impact of water deficit stress on nutritional quality and defense response of tomato genotypes. *Front. Plant Sci.* **2024**, *15*, 1403895. [CrossRef]
51. FAO. *Food Energy—Methods of Analysis and Conversion Factors*; FAO Food and Nutrition Paper 77; FAO: Rome, Italy, 2003.
52. Pomeranz, Y.; Meloan, C.E. *Food Analysis: Theory and Practice*, 3rd ed.; Aspen Publishers: Gaithersburg, MD, USA, 2000.
53. McDonald, P.; Edwards, R.A.; Greenhalgh, J.F.D.; Morgan, C.A.; Sinclair, L.A.; Wilkinson, R.G. *Animal Nutrition*, 7th ed.; Pearson Education: Essex, UK, 2011.
54. Onwuka, G.I. *Food Analysis and Instrumentation: Theory and Practice*; Naphtali Prints: Lagos, Nigeria, 2018; 489p.

55. Fageria, N.K. Nutrient interactions in crop plants. *J. Plant Nutr.* **2001**, *24*, 1269–1290. [CrossRef]
56. Nielsen, S.S. *Food Analysis*, 4th ed.; Springer: New York, NY, USA, 2010; 602p. [CrossRef]
57. Mepba, H.D.; Eboh, L.; Banigo, D.E.B. Effects of processing treatments on the nutritive composition and consumer acceptance of some Nigerian edible leafy vegetables. *Afr. J. Food Agric. Nutr. Dev.* **2007**, *7*, 1–18.
58. Asaolu, S.; Samuel, A.; Oyakilome, I.; Ajibulu, K.; Asaolu, M.F. Proximate and Mineral Composition of Nigerian Leafy Vegetables. *J. Food Res.* **2012**, *1*, 214–218. [CrossRef]
59. Marschner, H. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: London, UK, 2012; Volume 89, 651p.
60. Liu, R.H. Health-promoting components of fruits and vegetables in the diet. *Adv. Nutr.* **2013**, *4*, 384S–392S. [CrossRef]
61. Jimoh, M.O.; Afolayan, A.J.; Lewu, F.B. Suitability of *Amaranthus* species for alleviating human dietary deficiencies. *S. Afr. J. Bot.* **2018**, *115*, 65–73. [CrossRef]
62. Caunii, A.; Cuciureanu, R.; Zakar, A.M.; Tonea, E.; Giuchici, C. Chemical composition of common leafy vegetables. *Stud. Univ. Vasile Goldis Arad Ser. Stiintele Vietii* **2010**, *20*, 45–48.
63. Ebere, E.; Ihenetu, S.; Enyoh, E. Proximate and Mineral Composition of *Sesamum indicum* L. Seed. *Med. Anal. Chem. Int. J.* **2019**, *3*, 000152. [CrossRef]
64. Anyiam, P.N.; Phongthai, S.; Sai-Ut, S.; Kingwascharapong, P.; Jung, Y.H.; Zhang, W.; Rawdkuen, S. Nutritional Components and Digestibility Profiles of Some Potential Plant-Based Protein Sources. *Foods* **2025**, *14*, 1769. [CrossRef] [PubMed]