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Research Article

Assessment of the Potential Application of the Chameleon Soil Moisture Sensor to Grow the Upland Crop in the Mekong River Delta, Vietnam

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The increasing impacts of water scarcity and salinity intrusion in the Mekong River Delta (MRD) pose significant challenges to sustainable agricultural production, particularly during the dry season. This study evaluated the potential of the Chameleon soil water sensor as a tool to improve irrigation management for upland crops cultivated on former rice fields in the MRD. Three independent trials were conducted: (1) laboratory-based calibration for the sensor across three common soil textures of the MRD, (2) investigating the use of the Chameleon soil water sensor under varying salinity levels of irrigation water in the greenhouse condition, using beetroot (*Beta vulgaris* L.) as a test crop, and (3) the field assessment integrating the sensor with straw mulching for beetroot under real-world conditions. The results showed that the Chameleon soil water sensor demonstrated consistent sensitivity across sandy, clay loam, and silty clay soils, aligning well with van Genuchten-modeled soil water retention curves. In greenhouse conditions, sensor-guided irrigation reduced water use by 45.1%–53.8% compared to the farmer's daily irrigation practice (the control) treatment across increasing salinity levels (0, 0.5, and 1.0 g L^{-1}) of saline irrigating water, while maintaining comparable beetroot yields (up to 63.2 g pot^{-1}) and significantly improving water use efficiency (WUE), reaching values up to 4.71 kg m^{-3}. The field trial showed that combining the sensor with mulching stabilized soil moisture, improved chlorophyll content (58.35 SPAD), and reduced total irrigation by over 60% compared to the control. These findings confirm the Chameleon sensor's potential as a simple and practical tool for precision irrigation. Its integration with mulching offers a promising strategy for water conservation and salinity management in smallholder farming systems in the saline-affected areas in the MRD and similar environments.

Keywords: beetroot; chameleon sensor; Mekong river delta; salinity; soil moisture; water use efficiency

1. Introduction

Fast-growing global population and the increasing impacts of climate change have created critical challenges in many developing countries. Agriculture is the largest consumer of freshwater, competing with residential and industrial sectors for limited resources. As a result, the agricultural sector must produce more food using less water by improving crop water productivity. It is estimated that ~40% of crops in irrigated regions are vulnerable to disruptions in water supply [1, 2].

In Vietnam, the Mekong River Delta (MRD) is one of the country's most important agricultural regions, contributing over 50% of national rice production and a significant portion of exports. However, this region is increasingly affected by salinity intrusion, irregular rainfall, and rising sea levels, which have altered the hydrological balance and reduced freshwater

availability [3, 4]. The dry season typically begins in December and lasts through May, with canal water salinity and soil salinization peaking between March and late April [5, 6]. During this period, salinity intrusion extends 40–70 km inland; canal water salinity often exceeds 4 g L^{-1} (≈6.25 dS m^{-1}), depending on proximity to estuarine zones. The salinity level peaks in March–April before gradually declining when rainfall returns in May–June [7]. Consequently, freshwater scarcity during this period severely limits dry-season crop production. The intrusion of saline water became even more pronounced in 2020, surpassing the historical extreme of the 2015–2016 dry season in both salinity concentration and inland extent [8].

The cropping pattern in the MRD is traditionally dominated by two to three rice crops per year; however, dry-season fallowness has become increasingly common in saline-affected areas. In recent years, local farmers have begun to diversify into upland crops such as maize, mungbean, sesame, and vegetables to optimize land use and reduce risks associated with water shortage and salinity stress. These upland crops are generally established on former paddy fields with silty clay or clay loam soils of moderate fertility and low permeability, which retain residual moisture but are vulnerable to surface salinization during dry months. Understanding soil–water dynamics and salinity variation across these cropping periods is essential for developing improved irrigation and management practices in the region. Under such conditions, precise irrigation scheduling is vital to minimize both water wastage and salt accumulation in the root zone. While traditional irrigation scheduling relies on crop evapotranspiration (ETc) estimated from weather data and crop coefficients [9, 10], modern approaches increasingly depend on real-time soil and plant monitoring. The Chameleon soil water sensor, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) through the Virtual Irrigation Academy (VIA), provides a simple color-based indication of soil water tension: blue for wet (0 to −22 kPa), green for moderate (−22 to −50 kPa), and red for dry (≥ 50 kPa) [11]. This color system allows farmers to make irrigation decisions without complex calculations or technical expertise.

Despite its successful application in various contexts, the Chameleon sensor has not yet been widely studied in saline-affected soils or among smallholder farmers in the MRD, where alternating wet and dry cycles, shallow groundwater, and saline irrigation water strongly influence soil moisture dynamics [12, 13]. Assessing its accuracy and potential for improving water use efficiency (WUE) in such environments is therefore necessary.

Beetroot (*Beta vulgaris* L.), a root vegetable of the Amaranthaceae family, is widely cultivated in tropical and subtropical regions due to its adaptability and high nutritional value. As a halophytic-origin crop, *Beta vulgaris* exhibits moderate tolerance to salinity and drought stress [14–21]. Recent studies on *leaf beet* (*B. vulgaris var. cicla*) have further demonstrated its adaptive responses to saline conditions through morphological and physiological adjustments, including changes in leaf area, tissue density, and water-relation traits under NaCl concentrations up to 0.7% [22–25]. In Vietnam, beetroot is typically grown during the dry season in southern provinces. However, beetroot cultivation systems have recently been adversely affected by salinity intrusion and freshwater shortages during the dry season [26]. Given its short growth duration (90–100 days), ease of cultivation, and increasing market demand in peri-urban areas, beetroot was selected as the test crop for evaluating sensor-based irrigation management and water-use efficiency under saline-affected conditions in the MRD. Therefore, this study aimed to evaluate the effectiveness of the Chameleon soil water sensor in improving irrigation WUE for beetroot cultivated in saline-affected conditions during the dry season in the MRD. Specifically, we investigated whether sensor-based irrigation could reduce water use while maintaining crop yield, compared to conventional daily irrigation practiced by local farmers.

2. Materials and Methods

2.1. Experimental Design. This experiment was conducted into three separate trials to assess the potential application of the Chameleon sensor on the upland crop cultivation under water scarcity and saline intrusion in the MRD, Vietnam. Each trial addressed a specific research objective, progressing from controlled conditions to real-world field application.

The first trial (Trial 1) aimed to evaluate the accuracy and sensitivity of the Chameleon sensor across the dominant soil textures of the MRD. These textures are typical of agricultural zones that are seasonally prone to salinity, but salinity itself was not included as an experimental factor in this trial. Trial 1 was conducted under freshwater irrigation to isolate soil texture effects. The second trial (Trial 2) investigated the use of the Chameleon sensor for optimizing irrigation scheduling under varying salinity levels of irrigation water in the greenhouse environment, using beetroot (*Beta vulgaris* L.) as a test crop. The third trial (Trial 3) assessed the effectiveness of sensor-based irrigation compared to traditional farmer practices in the field trial, with and without the addition of straw mulch.

2.2. Materials and Methods

2.2.1. Trial 1: Assessment of the Chameleon Sensor Sensitivity and Performance in Different Soil Textures of the MRD. This trial was implemented from October to November 2022 to assess the sensitivity and accuracy of the Chameleon sensor across different soil textures of the MRD. Topsoil samples (0–20 cm depth) were collected from three representative agricultural locations. Although these landscapes are agrologically associated with seasonal saline intrusion, the collected soils were not saline, and the trial was conducted entirely under nonsaline water irrigation (<0.05 dS m^{-1}). This ensured that soil texture was the only intended factor influencing sensor performance.

The selected soil textures included sand, clay loam, and silty clay, which were analyzed following the Robinson pipette method and soil taxonomy [27]. Soil water retention curves (pF curves) of these soil textures were determined experimentally following Cassel and Nielsen [28]. The retention was

measured at seven matric potential (pF) values (0, 1, 1.5, 1.8, 2, 2.5, 2.8) and fitted to the van Genuchten model [29].

For the sensor evaluation, after building the pF curves, soil samples were placed into 4 kg pot^{-1} with three replications per soil texture. The Chameleon sensor was installed vertically at a depth of 0–15 cm in each pot. Irrigation water was applied until the sensor light indicated "blue" (0 to −22 kPa). Soil moisture was recorded every 2 h as the soil dried until the sensor changed to "green" (−22 to −50 kPa) and "red" (> −50 kPa), respectively.

To compare sensor readings with laboratory reference data, the pF values were converted to matric potential values expressed in kilopascals (kPa), where:

$$\psi m(\text{kPa}) = 10^{pF}/102(1\ \text{kPa} = 102\ \text{cm of water head})$$

The volumetric water content values derived from the pF curves at the time points when the sensor light changed colors were then compared to the soil moisture readings indicated by the Chameleon sensor to evaluate its accuracy and sensitivity.

2.2.2. Application of the Chameleon for Irrigation Water Management in Cultivation of Beetroot on Saline-Affected Soil Condition

2.2.2.1. Trial 2: Greenhouse Evaluation Under Saline Irrigation Conditions. This trial was implemented in a greenhouse from November 2022 to February 2023 to assess the ability of the Chameleon sensor to guide irrigation in saline-affected conditions using beetroot (*Beta vulgaris* L.) as a model crop. The greenhouse had a semi-controlled environment with natural light and ventilation. During the experimental period, average day/nighttime temperatures was 35.7/27.7°C, with relative humidity varying between 55.5% and 86.9%. No artificial lighting or heating was used. The structure was covered with polyethylene film to prevent direct rainfall, and natural light was the sole source of illumination. The experiment aimed to determine whether sensor-based irrigation could reduce water use while maintaining crop performance under varying levels of irrigation water salinity.

Saline water used for this trial was seawater from Soc Trang province, Vietnam, where the third trial was established. The seawater was diluted with fresh water in the greenhouse to achieve the desired concentration. The freshwater used for dilution was supplied from the irrigation system of the net-house facility at Can Tho University, which is routinely filtered, sterilized, and pH-adjusted to standard levels (pH 6.5–7.0) before being used in experiments. This ensured that the water quality remained consistent and free from contaminants that could interfere with the treatments.

The experimental soil was classified as Salic Fluvisols [1] with a silty clay texture (Soil Survey Staff, 1998), which is the common soil texture in the experimental region. Soil samples were collected from 0 to 20 cm depth in a rice field in Long Phu District, Soc Trang province, Vietnam (9.582275, 106.130260). This area is frequently affected by seawater intrusion and typically remains fallow during the dry season. The soil was air-dried, homogenized, and sieved. Eight (08) kilograms of dry soil were placed in cylindrical plastic pots (27 cm diameter × 30 cm height). Chameleon sensors were vertically installed at a depth of 15 cm and positioned one-third from the center of the pot.

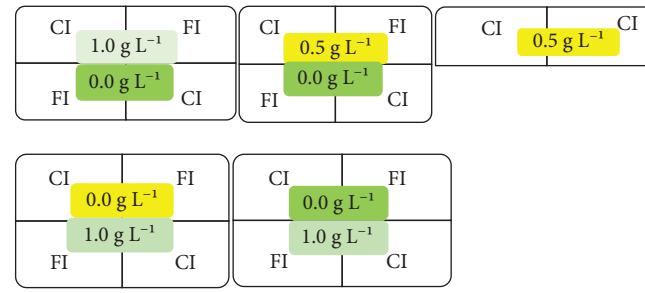


Figure 1: Experimental layout for evaluating saline irrigation management strategies affected on the growth and yield of beetroot.

Irrigation water used for the greenhouse experiments was obtained from two sources: freshwater (0 dS m^{-1}) from the domestic water supply system within the greenhouse area, and saline water collected from seawater sources. Saline water was diluted in storage tanks and adjusted to designated salinity levels of 0.5 g L^{-1} and 1.0 g L^{-1} which were used to simulate the early dry-season conditions of the MRD, where slightly saline water may be encountered by farmers. These concentrations were selected not to impose strong salinity stress, but to evaluate whether cumulative salt input over the crop cycle interacts with irrigation volume. An ECe meter was used to verify salinity levels prior to irrigation, ensuring that the solutions matched the required treatment levels before being applied to beetroot.

Beetroot seeds (variety Bohan F1 from the Bejo company), known for their tolerance to salt and drought, which have been successfully grown in many areas with similar conditions as the MRD, but have not been grown in the MRD before. Beetroot were sown at three plants per pot, and the experiment followed a completely randomized design (CRD) with two factors:

- Factor A—irrigation methods: Chameleon sensor-based irrigation (CI), applied when the sensor light turned red (> −50 kPa) and stop irrigating when the light turned blue (0 to −22 kPa); Farmer daily irrigation practice (the control), applied once per day at a fixed frequence, following common farmer practice in the MRD. The daily irrigation volume ranged from 350 to 450 mL pot^{-1} day^{-1} over the crop cycle by using a measuring cup.
- Factor B—salinity levels of irrigation water: 0.0 g L^{-1}(nonsaline), 0.5 g L^{-1}, and 1.0 g L^{-1}. In total, six treatments were set up, each was replicated three times, as illustrated in Figure 1. The fertilizer rate applied in the experiments was 105 N −60 P_2O_5−150 K_2O (kg ha^{-1}) and was converted to the area of the experimental pots. Pest control measures were implemented as needed.

2.2.2.2. Trial 3: Field Evaluation of Sensor-Based Irrigation Compared to Farmer Practice Under Mulching Conditions. This field trial was conducted from February to May 2023 to

assess the performance of Chameleon sensor-guided irrigation in a real farm setting under saline-affected conditions of the dry season. The trial was designed to evaluate both the individual and combined effects of sensor-guided irrigation and straw mulching on water use and crop growth. The experiment was carried out on soil previously cultivated with two rice crops per year (winter–spring and summer–autumn seasons) using high-yielding rice varieties, located in Nuoc Man 2 Hamlet, Long Phu commune, Long Phu district, Soc Trang province, Vietnam (coordinates: *X* 9.582275; *Y* 106.130260).

The experiment followed a randomized complete block design (RCBD) with three irrigation treatments and four replicates:

- Treatment 1 (CI-nonmulching): Irrigation based on the Chameleon sensor without mulching to assess only the impact of sensor-based irrigation.
- Treatment 2 (CI-mulching): Irrigation based on the Chameleon sensor combined with straw mulching to examine whether the addition of mulch on maintaining soil moisture and yield outcome.
- The control treatment (FI-mulching): Traditionally daily farmer irrigation with straw mulching; farmers apply water daily regardless of soil moisture status, reflecting common farmer practice in the region.

Beetroot (Bohan F1) was grown in all plots. The soil was similar in texture to Trial 2 (silty clay) and subject to saline conditions during the dry season 2023. Straw mulch was uniformly applied to the soil surface in mulched plots. All plots received the same fertilization and crop care regime as Trial 2.

2.3. Sampling and Analysis. The first trial: soil sample (0–15 cm) was collected at the time when the sensor light changed color to measure volumetric water content.

The second and third trials were collected parameters include:

- Irrigation metrics: total volume of water applied (WA, $m^3\,ha^{-1}$), frequency of irrigation.
- Soil parameters (0–15 cm): moisture content (%), electrical conductivity (ECe, $dS\,m^{-1}$), total dissolved salt (TDS) ($mg\,L^{-1}$). Soil sampling occurred once every 15 days.
- Plant growth and agricultural parameters: plant height (cm), leaf length (cm), leaf width (cm), and SPAD index were recorded at 70 days after sowing (DAS). Yield and quality: root diameter, tuber yield, and brix values (sugar content) were measured at harvest.
- The WUE was calculated as the kilograms of beetroot yield per cubic meter of applied water for different treatments using the following Equation [30]:

$$\mathrm{WUE}(\mathrm{kg\,m^{-3}}) = \frac{\text{Root yield } (\mathrm{kg\,ha^{-1}})}{\text{Total water applied } (\mathrm{m^3\,ha^{-1}})}.$$

- Soil ECe was measured using an ECe meter (Horiba B-173). $ECe_{1:5}$ values were converted to ECe using a factor of 8.6 for soils with 35% to 40% clay content [31–33]. Total dissolved solids (TDS) were estimated by multiplying ECe ($dS\,m^{-1}$) by 0.64 [34]

2.4. Stastistical Analysis. The study used Microsoft Excel software for descriptive statistics to input research data and to design charts illustrating the comparison of differences between experimental treatments. Results are presented as mean values ± standard deviations (SDs) calculated from sample replicates. The mean differences between experimental treatments were statistically calculated using multifactor analysis of variance (General Linear Model-ANOVA) following a CRD for the second trial and an RCBD for the third trial. Independent samples *T*-tests were conducted to compare paired treatments in Trial 1. All statistical analyses were performed using Minitab software version 20.0. Mean differences between treatments were compared using Tukey's test at a significance level of $p \leq 0.05$.

3. Results

3.1. Sensor Sensitivity Across Soil Textures of the MRD. Figure 2 illustrated the soil water retention curves for three soil texture types: silty clay, clay loam, and sand. The soil water retention data, represented as soil moisture percentage, is plotted against hydraulic head (pF) values. The pF values between the two vertical dark blue lines (from −10 to −33 kPa) indicated the field capacity (FC), which represented the range of soil moisture where plants can effectively extract water. The results (Figure 2) indicated that the two types of soil textures, silty clay, and clay loam, have similar curve shapes, with the highest moisture content at the value of pF0 (0 kPa) to the value of pF2 (−10 kPa), while sandy texture showed poor water retention capacity.

According to VIA, the display light of the Chameleon sensor is blue when the pF value is in the range of 0 to −22 kPa. Corresponding to that pF value, the volumetric moisture content of soil (Figure 2) with silty clay texture ranged from 35% to 53%, clay loam texture ranged from 33% to 46%, the sand texture had a value ranging from 10% to 37%. The sensor light changes from blue to green, corresponding to the pF value of −25 to −50 kPa (via.farm). The corresponding volumetric moisture content in soils with silty clay was from about 30% to 35%, clay loam was from about 27% to 33% and sandy texture has a volumetric moisture content of about 8%–10%. The volumetric moisture content is lower than the above value ranges, the sensor display light turns red.

The sensitivity evaluation of the Chameleon sensor across three soil textures showed distinct volumetric moisture ranges for its blue, green, and red-light signals (Figure 3). For silty clay, moisture content ranged from 47% to 36% (blue), 34%–27% (green), and below 27% (red). For clay loam, it ranged from 41% to 32% (blue), 32%–27% (green), and below 27% (red). For sandy soil, moisture levels were lower, ranging from 37 to 16% (blue), 15% to 8% (green), and below 8% (red). Comparing these results to the pF curves (Figure 2), the sensor accurately reflected soil moisture dynamics and retention capacity for all textures, but the response time of color change was different, particularly in sandy soil (significantly slower).

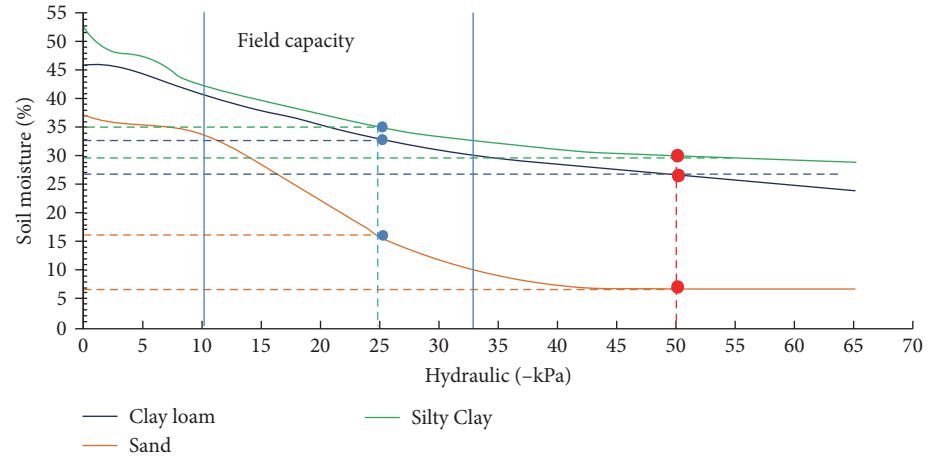


Figure 2: Water retention curves of three different soil textures of the MRD, Vietnam. *Note:* Between the two blue lines is the field water capacity. Blue dot: is the intersection point where the display light changes from green (−22 to 50 kPa) to blue (0 to −22 kPa). Red dot: is the intersection point where the display light changes from red (> −50 kPa) to green.



Figure 3: Volumetric soil moisture and sensor color changes for the Chameleon sensor across three different soil textures.

Table 1: Effects of the Chameleon sensor and saline irrigation water on soil moisture content.

Factors		Soil moisture (%)						
		15 DAS	30 DAS	45 DAS	60 DAS	75 DAS	90 DAS	105 DAS
Irrigation methods (*A*)	CI	28.3^{a}	27.1	26.0	26.7^{b}	28.0	31.2	33.8
	FI	27.3^{b}	31.7	24.3	32.6^{a}	28.1	28.9	31.6
Salinity levels (*B*)	0.0 g L^{-1}	28.4^{b}	31.6^{ab}	27.4	30.4	29.9	30.8	35.6
	0.5 g L^{-1}	25.3^{c}	24.0^{b}	24.4	30.5	24.9	29.9	31.7
	1.0 g L^{-1}	29.7^{a}	32.6^{a}	23.7	28.2	29.3	29.4	30.8
p-(*A*)Value		**	ns	ns	*	ns	ns	ns
p-(*B*)Value		**	*	ns	ns	ns	ns	ns
p-(*A* × *B*)Value		**	*	ns	ns	ns	ns	ns

Note: Means with different following superscript letters indicate statistically significant differences at the 5% level according to Tukey's test; (*) indicates $p \leq 0.05$; (**) indicates $p < 0.01$; (ns) indicates no statistically significant difference; CI, Chameleon irrigation method; FI, farmer daily irrigation method.

3.2. Evaluation of the Effect of the Chameleon Sensor on WUE and the Beetroot Growth Under Saline Irrigation Conditions in Greenhouse

3.2.1. Soil Moisture Content. Soil moisture contents of the treatments were measured at seven time points from 15 to 105 DAS to evaluate the influence of irrigation methods and salinity levels (Table 1). Significant differences between irrigation methods were observed at 15 DAS ($p \leq 0.01$) and 60 DAS ($p \leq 0.05$). At 15 DAS, the treatments under Chameleon sensor-based irrigation (CI) maintained significantly higher soil moisture (28.3%) compared to the farmer's daily irrigation practice (FI, 27.3%), highlighting its efficiency in early crop stages. In contrast, at 60 DAS, FI-treated pots retained significantly more moisture (32.6%) than those irrigated using the sensor (26.7%). Despite these differences, no

Table 2: Effects of the Chameleon sensor and saline irrigation water on soil moisture content at 15 DAS and 30 DAS.

Treatments	Soil moisture (%)	
	15 DAS	30 DAS
$CI_{0.0}$	28.4 ± 0.5^{b}	34.1 ± 2.8^{ab}
$CI_{0.5}$	28.0 ± 0.5^{b}	26.2 ± 0.8^{b}
$CI_{1.0}$	28.4 ± 0.1^{b}	28.1 ± 0.7^{b}
$FI_{0.0}$	28.4 ± 0.1^{b}	29.2 ± 0.8^{ab}
$FI_{0.5}$	22.7 ± 0.5^{c}	26.0 ± 3.3^{b}
$FI_{1.0}$	30.9 ± 0.9^{a}	40.2 ± 2.2^{a}
p-Value	**	*

Note: Means with different following superscript letters indicate statistically significant differences at the 5% level according to Tukey's test; (*) indicates $p \leq 0.05$; (**) indicates $p \leq 0.01$; (ns) indicates no statistically significant difference. $_{0.0,}$ nonsaline, $_{0.5}$, 0.5 g L^{-1}; $_{1}$, 1.0 g L^{-1} of salinity levels of irrigation water applied; CI, Chameleon irrigation method; FI, farmer daily irrigation method.

statistically significant variations were observed at later stages (75–105 DAS), which can be attributed to the sensor's ability to operate continuously and provide precise, visual information on soil moisture content, enabling timely and efficient water supplementation. This ensures optimal and stable moisture levels for crops, particularly under limited freshwater conditions.

Significant effects of salinity levels on soil moisture were also detected at 15 and 30 DAS. At 15 DAS, the 1.0 g L^{-1} salinity treatment resulted in the highest moisture content (29.7%), followed by the 0.0 g L^{-1} (28.4%) and 0.5 g L^{-1} (25.3%) treatments. Similarly, at 30 DAS, the highest moisture was observed under the 1.0 g L^{-1} treatment (32.6%), while the 0.5 g L^{-1} treatment had the lowest (24.0%). These findings may be attributed to reduced water uptake or evaporation under higher salinity conditions.

Moreover, as can be seen in Table 2, at 15 DAS, the highest soil moisture was recorded in the $FI_{1.0}$ treatment (30.9%), significantly higher than all other treatments ($p \leq 0.01$), while the lowest moisture was found in $FI_{0.5}$ (22.7%). In contrast, the Chameleon sensor-controlled treatments (CI) maintained relatively stable soil moisture levels across salinity conditions (28.0%–28.4%), suggesting precise irrigation regulation. By 30 DAS, FI treatments again showed the fluctuation of soil moisture from 26.0% to 40.2%, whereas CI treatments maintained from 26.2% to 31.1%, demonstrating the Chameleon sensor's effectiveness in regulating irrigation to maintain adequate soil moisture.

3.2.2. Water Consumption and Water Use Efficiency. The recorded irrigation volumes showed significant differences between the irrigation methods across all salinity levels (Figure 4a). The total WA under the control (the farmer's daily irrigation method; FI) averaged 21.7 L^{-1} pot throughout the growing period. In contrast, the Chameleon sensor-based irrigation treatments (CI) used significantly less water, with final irrigation volumes ranging from 10.0 to 11.9 L^{-1}pot depending on the salinity level. The percentage reductions in water use for the CI treatments compared to FI were 45.1%, 51.2%, and 53.8% under 0.0 g L^{-1}, 0.5 g L^{-1} and 1.0 g L^{-1} salinity levels, respectively.

The WUE results are presented in Figure 4b. Across all salinity levels, WUE was consistently higher in CI treatments than in FI treatments. The WUE values for CI increased progressively with salinity, reaching 3.54 kg m^{-3} at 0.0 g L^{-1}, 4.22 kg m^{-3} at 0.5 g L^{-1}, and 4.71 kg m^{-3} at 1.0 g L^{-1}.

3.2.3. TDS in Soil. The accumulation of TDSs in the soil was assessed at two time points: the initial stage and the end of the crop (Table 3). As expected, the applied salinity levels were mild and did not induce drastic changes in soil TDS ($p > 0.05$) during the early stages. However, a gradual increase in TDSs was observed toward the end of the crop cycle, particularly under the FI treatment, reflecting cumulative salt loading when irrigation volumes were high.

3.2.4. Growth Parameters and Yield of the Crop. The growth and yield indicators of beetroot under different irrigation methods and salinity levels are presented in Table 4. No statistically significant differences ($p > 0.05$) were observed between the Chameleon sensor-based irrigation and the control in terms of plant height, leaf length, leaf diameter, chlorophyll content (SPAD), Brix index, or root yield.

However, salinity level had a significant effect on chlorophyll content ($p \leq 0.05$) and sugar content ($p \leq 0.01$). Treatments irrigated with 1.0 g L^{-1} salinity showed the highest chlorophyll content (58.72 SPAD units), followed by 0.5 g L^{-1} (54.95), and 0.0 g L^{-1} (50.05). Similarly, Brix values were significantly higher in the 0.5 and 1.0 g L^{-1} treatments (10.00% and 9.53%, respectively), compared to the 0.0 g L^{-1} treatment (6.37%). Although root yield did not differ significantly among treatments, the 1.0 g L^{-1} salinity treatment under CI tended to produce a slightly higher yield (63.2 g pot^{-1}) than other treatments.

3.3. Application of the Chameleon Sensor in Improving WUE for Upland Crop Cultivation on the Rice Field Soil During the Dry Season in the MRD

3.3.1. Soil Moisture, Salt Accumulation, and Water Use Efficiency. This section examined the potential of the Chameleon sensor for managing irrigation in beetroot—the representative of upland crops cultivated during the dry season on the rice paddy fields.

Figure 5 illustrated the soil moisture dynamics, TDS accumulation, and water usage across treatments combining different irrigation methods and mulching practices. While no statistically significant differences were observed among treatments, several consistent trends emerged.

In the farmer-managed daily irrigation with mulching (FI-Mulching), soil moisture levels were generally higher than those in both Chameleon-controlled irrigation treatments (CI-Non mulching and CI-Mulching). During the early growth stages (0–40 DAS), soil moisture in this treatment remained between 37% and 39%, gradually decreasing toward the end of the cycle in response to plant water uptake.

The Chameleon-controlled irrigation without mulching showed consistently lower soil moisture levels compared to other treatments yet remained within the soil's FC threshold as established in Trial 1. The Chameleon-controlled irrigation with mulching demonstrated the most stable soil moisture

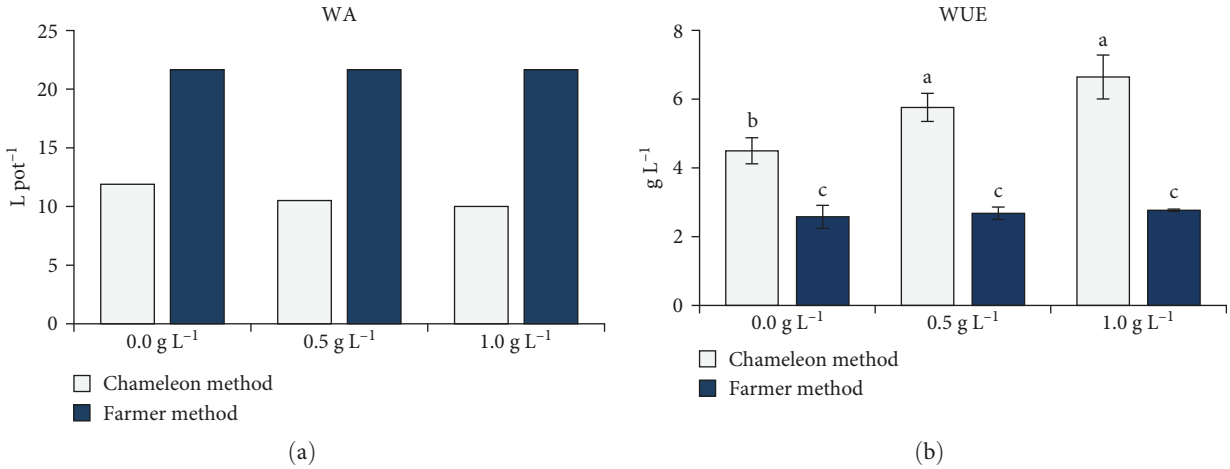


Figure 4: Effect of salinity levels on total water applied (a) and water use efficiency (b) among treatments.

Table 3: Effects of irrigation methods and saline irrigation on the accumulation of total dissolved salts in soil.

Factors		Total dissolved salts (g L^{-1})	
		Initial of crop	End of crop
Irrigation methods (*A*)	CI	0.92	4.97
	FI	0.98	5.42
Salinity levels (*B*)	0 0.0 g L^{-1}	0.93	4.35
	0.5 g L^{-1}	0.90	5.23
	1.0 g L^{-1}	1.01	6.01
p-(*A*)Value		ns	ns
p-(*B*)Value		ns	ns
p-(*A* ×*B*)Value		ns	ns

Note: Data means with different following letters indicate statistically significant differences at the 5% level according to Tukey's test; (ns) indicates no statistically significant difference; CI, Chameleon irrigation method; FI, farmer irrigation method.

levels throughout the crop cycle. The combination of sensor-based irrigation and mulching revealved both reduced evaporation losses and enhanced water retention. Notably, this treatment used less than 60% of the irrigation volume applied in CI-Nonmulching and FI-Mulching treatments while achieving comparable or superior soil moisture conditions (Figure 5c), thereby improving WUE substantially. TDS changes (Figure 5b) revealed that both CI-Nonmulching and FI-Mulching experienced greater salt accumulation in the topsoil surface (root zone) compared to CI-Mulching. This could be attributed to multiple factors: (1) the higher use of saline irrigation water, (2) increased surface evaporation without mulch, which concentrates salts in the upper soil layers, and (3) overirrigation in FI-Mulching, which may have caused uneven salt leaching or shallow salt redistribution. In contrast, CI-Mulching effectively minimized salt accumulation by preserving stable moisture conditions and limiting excessive evaporation, thus applying less irrigation water.

3.3.2. Growth Parameters and Yield of Beetroot. The CI-Mulching treatment exhibited the most favorable agronomic outcomes, with significantly greater plant height (35.18 ± 2.1 cm), leaf length (25.63 ± 0.9 cm), leaf diameter (12.38 ± 0.6 cm), fresh biomass (14.45 ± 0.7 tons ha^{-1}), chlorophyll content (58.35 ± 3.1 SPAD), and tuber yield (36.17 ± 2.9 tons ha^{-1}) compared to CI-Non mulching. The FI-Mulching treatment performed similarly to CI-Mulching in most parameters but did not differ significantly in tuber yield or fresh biomass.

The CI-Non mulching treatment consistently showed the lowest values for growth and yield parameters, particularly in leaf size, biomass accumulation, and yield (19.35 ± 1.6 tons ha^{-1}). Despite using less irrigation water (as shown in earlier sections), the absence of mulching likely limited its efficiency in promoting optimal growth.

The Brix index showed no significant difference among treatments, indicating that soluble sugar content was unaffected by irrigation methods or mulching practices under the experimental conditions. These results indicate that the combination of Chameleon sensor-based irrigation and mulching significantly enhances beetroot growth and yield, likely through improved water retention and reduced evaporative loss.

4. Discussion

4.1. Accuracy and Sensitivity of the Chameleon Sensor Across Soil Textures of the MRD. The results from Trial 1 demonstrated that the Chameleon sensor effectively responded to changes in soil moisture across different soil textures commonly found in the MRD. Its color-coded output corresponded well with measured volumetric moisture content and theoretical retention patterns depicted in the soil water retention (pF) curves. In finer-textured soils containing silty clay and clay loam, the sensor's transition thresholds—blue (wet), green (moist), and red (dry)—aligned closely with FC and wilting point ranges, suggesting that the sensor can reliably guide irrigation decisions under such conditions.

However, in coarse-textured soils as sandy soil, while the sensor's color changes generally tracked with moisture decline, a notable delay in response time was observed, especially during the transition from green to red. This lag is attributed to

Table 4: Growth and yield of beetroot under different irrigation methods.

Factors		Plant heigh (cm)	Leaf length (cm)	Leaf diameter (cm)	Chlorophyll content	Brix (%)	Tuber yield (g pot^{-1})
Irrigation methods (*A*)	CI	24.77	21.61	7.96	55.66	8.78	60.1
	FI	25.11	21.22	8.17	53.49	8.49	57.9
Salinity levels (*B*)	0 0.0 g L^{-1}	26.57	22.75	8.58	50.05c	6.37c	54.6
	0.5 g L^{-1}	23.42	29.50	7.63	54.95b	10.00a	59.2
	1.0 g L^{-1}	24.83	21.00	7.97	58.72a	9.53b	63.2
p-(*A*)Value		ns	ns	ns	ns	ns	ns
p-(*B*)Value		ns	ns	ns	*	**	ns
p-(*A* × *B*)Value		ns	ns	ns	ns	ns	ns

Note: Data means with different following letters indicate statistically significant differences at the 5% level according to Tukey's test; (*) indicates $p \leq 0.05$; (**) indicates $p \leq 0.01$; (ns) indicates no statistically significant difference. CI, Chameleon irrigation method, FI, farmer daily irrigation method— the control.

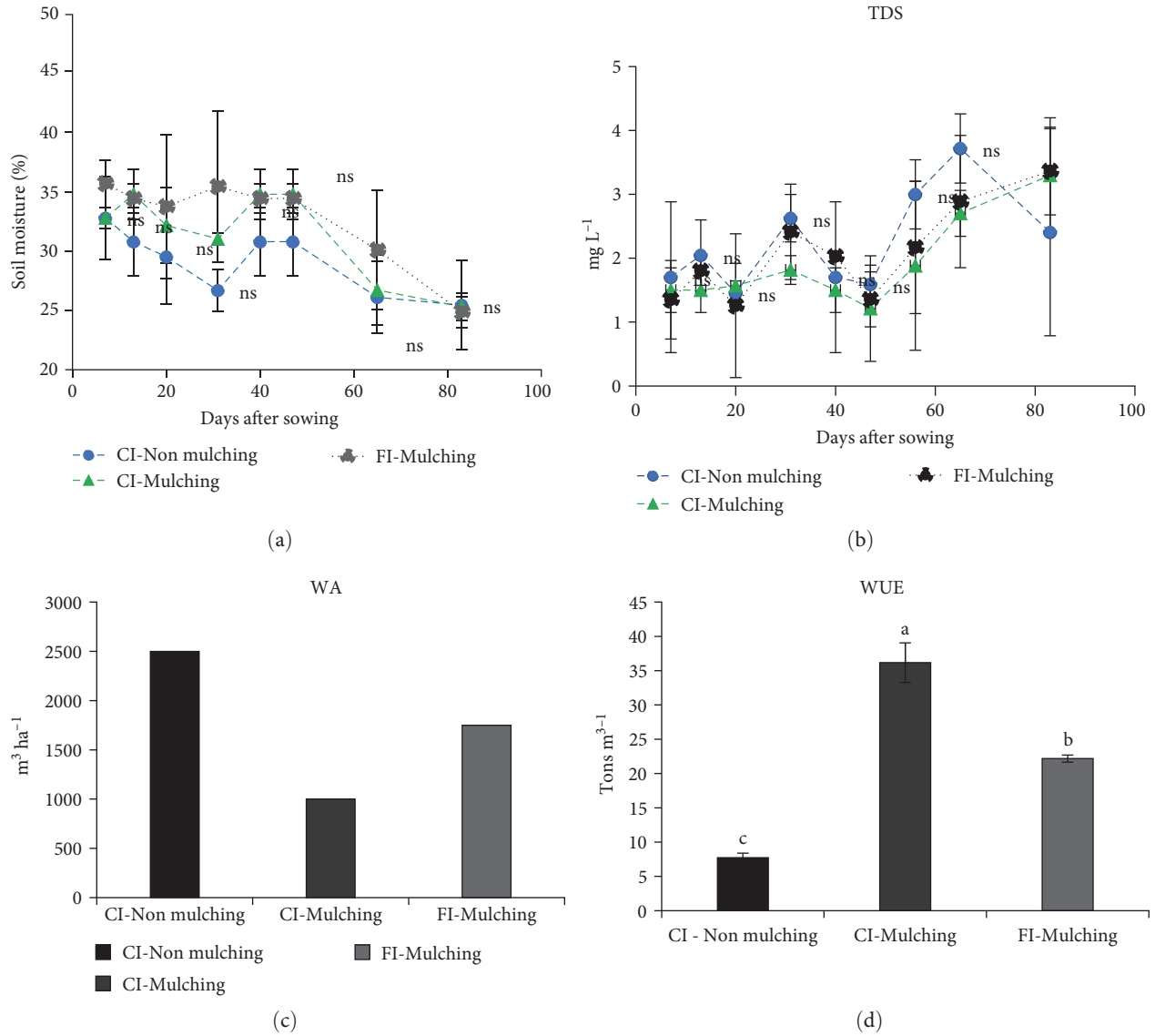


Figure 5: Effects of irrigation methods on soil moisture (a), salt accumulation (b), total water applied (c), and water use efficiency (d).

the rapid infiltration and low water-holding capacity of sandy soils, which can cause the sensor to temporarily overestimate moisture content. Experimental studies by Vereecken et al. [35] observed fingered infiltration fronts in dry sandy media—where water advances via narrow channels rather than uniformly—leading to delayed moisture homogenization compared to finer-textured soils. Furthermore, large-scale soil moisture monitoring initiatives have shown that coarse-textured soils equilibrate more slowly following wetting events than fine-textured counterparts [35, 36]. This dual evidence supports the interpretation that in sandy fields, the Chameleon sensor may exhibit a time lag in color transitions, necessitating cautious calibration and interpretation in such environments.

Despite this limitation, the Chameleon sensor remains a cost-effective, farmer-friendly tool for real-time soil moisture monitoring in the MRD, particularly in the dominant alluvial and clay-rich soils where its performance has proven satisfactory. However, given the observed time-lag effects in sandy soils, further field-based evaluations under sandy soil conditions are warranted. These trials would support more precise calibration of sensor thresholds and improve confidence in its interpretation across diverse soil textures. Integrating such efforts will enhance the reliability of sensor-guided irrigation decisions and prevent misinterpretation in coarse-textured environments.

4.2. Enhancing WUE Under Saline Affected Conditions. In Trial 2, the Chameleon sensor contributed to a significant reduction in irrigation water across salinity levels ($0.5\,g\,L^{-1}$ and $1.0\,g\,L^{-1}$), as shown in Figure 4a, demonstrating its potential for improving WUE. Treatments with sensor-based irrigation used 45%–54% less water than the farmer-controlled method. Despite reduced water volumes, crop performance remained stable, suggesting that precise irrigation scheduling is crucial under saline conditions to mitigate the risk of salt accumulation.

Although the applied irrigation salinity ($0.5–1.0\,g\,L^{-1}$) was well within the tolerance range of beetroot, the slightly elevated TDS values observed toward harvest indicate that even mild salinity can accumulate in the soil when irrigation volumes are high. This highlights the importance of managing not only water quantity but also the cumulative salt input associated with irrigation practices. These findings echo previous studies that emphasized strategic irrigation control can conserve water while maintaining yield in salt-affected environments [37]. The resulting WUE increased progressively with salinity under sensor-based irrigation, and the highest value of WUE was $4.71\,kg\,m^{-3}$ at $1.0\,g\,L^{-1}$(Figure 4b). This suggests that mild salinity may stimulate water-saving physiological mechanisms such as osmotic adjustment and stomatal regulation, thereby improving water productivity [38–40]. However, it is important to note that this trend may not persist at higher salinity levels. If irrigation water salinity continues to increase beyond $1.0\,g\,L^{-1}$, WUE could potentially decline due to osmotic stress, reduced root water uptake, or salt toxicity that limits crop growth and metabolic function [38, 41]. High salinity can impair membrane integrity, reduce photosynthetic activity, and alter water relations in sensitive crops, offsetting the benefits of water-saving strategies. Therefore, further studies under more severe salinity conditions are recommended to determine the critical threshold beyond which sensor-based irrigation becomes ineffective or counterproductive [37, 42].

In Trial 3, similar improvements in WUE were observed under real field conditions when the sensor was combined with mulching (CI-Mulching), as shown in Figure 5c,d. This treatment used over 60% less irrigation water while maintaining high beetroot yield, confirming the sensor's effectiveness under saline stress and highlighting the synergistic benefit of combining precision irrigation with traditional soil moisture conservation practices. As noted by Pardossi et al. [9], frequent over-irrigation without accounting for leaching requirements can accelerate this effect. The combination of precision irrigation and straw mulch in this study effectively mitigated these risks. These findings are also consistent with previous studies showing that straw mulching can significantly reduce evaporative losses, enhance soil water retention, and improve crop water productivity under saline or arid conditions [5, 43].

4.3. Soil Salt Accumulation Dynamics Under Different Irrigation Methods. Although sensor-based irrigation reduced water input and irrigation frequency, a slight increase in soil TDS was observed compared to the farmer method, particularly in the middle stage of the crop (Table 3). This finding may be attributed to less leaching under sensor-guided irrigation, which used lower water volumes. As noted by Rhoades et al. [44] a reduced leaching fraction can promote salt accumulation, even when irrigation water has even low salinity levels.

However, the absence of significant yield reduction confirms that the salinity levels used in Trial 2 were too mild to impose direct physiological stress on beetroot. Instead, the relevance of salinity in this experiment lies in its cumulative contribution to soil salt load. Because the FI treatment used considerably more irrigation water, it also introduced a higher total amount of dissolved salts into the soil over time. In contrast, sensor-guided irrigation, by reducing total water input, effectively limited the cumulative salt applied to the root zone, helping maintain salinity within the crop's tolerance range.

Overall, the minimal salt accumulation indicates that Chameleon sensors can be applied without compromising soil health, provided leaching strategies are incorporated when irrigation water salinity is higher [29]. These findings highlight the importance of managing not only irrigation volume but also the cumulative salt load associated with long-term use of even mildly saline water.

4.4. Effects on Plant Growth and Yield. In both greenhouse and field experiments (Tables 4 and 5), no significant differences were observed between irrigation methods for most growth parameters and yield; this means that reduced water input using the Chameleon sensor did not adversely affect crop performance. Beetroot maintained comparable yields under CI and FI treatments, demonstrating the feasibility of reducing water inputs without compromising productivity [41].

Table 5: Growth and yield of beetroot.

Treatments	Plant heigh (cm)	Leaf length (cm)	Leaf diameter (cm)	Fresh biomass (tons ha^{-1})	Chorophyll content	Brix index (%)	Tuber yield (tons ha^{-1})
CI-Non mulching	30.3 ± 0.9^{b}	21.9 ± 1.9^{b}	10.5 ± 1.1^{b}	12.5 ± 0.6^{b}	46.3 ± 2.9^{b}	9.4 ± 0.1	19.4 ± 1.6^{b}
CI-Mulching	35.2 ± 2.1^{a}	25.6 ± 0.9^{a}	12.4 ± 0.6^{a}	14.5 ± 0.7a	58.4 ± 3.1^{a}	9.5 ± 0.1	36.2 ± 2.9^{a}
FI Mulching	33.3 ± 1.5^{ab}	26.1 ± 1.3^{a}	12.6 ± 1.0^{a}	14.9 ± 0.7a	57.01 ± 2.5^{a}	9.4 ± 0.9	38.8 ± 0.9^{a}
p-Value	**	**	*	**	**	ns	**

Note: Data means with different following superscript letters indicate statistically significant differences at the 5% level according to Tukey's test; (*) indicates $p \leq 0.05$; (**) indicates $p \leq 0.01$; (ns) indicates no statistically significant difference. CI, Chameleon-controlled irrigation method; FI, Farmer daily irrigation method.

Interestingly, salinity treatments (0.5 and 1.0 $g\,L^{-1}$) resulted in higher chlorophyll and brix index values, suggesting osmotic adjustment responses in beetroot under mild saline stress, as observed in prior studies on salinity and chlorophyll content in salt-tolerant crops [13, 45, 46]. These results indicate that mild salinity may enhance certain physiological parameters, a phenomenon also reported in salt-tolerant crops like sugar beet [47–49]. While the present study focused on mild salinity levels (0.5 and 1.0 $g\,L^{-1}$) which are typical of the slightly saline irrigation water encountered in many areas of the MRD, it is important to consider beetroot performance under higher salinity conditions. The lowest threshold level of irrigation water ECw not restricting crop growth was 0.7 dS m^{-1}, lower than ECe (1 dS m^{-1}) [50]. The majority of vegetable crops present low tolerance to saline water applied continuously. The majority of vegetable crops have a salinity threshold that is $\leq$2.5 dS m^{-1} [51]. Thus, the area of soils with restrictions for vegetable crop production is certainly greater than the area of salinized soils, since a saline soil is generally defined as showing an ECe value of the saturation extract (ECe) in the root zone that exceeding 4 dS m^{-1}. Previous studies in the MRD and other mega deltas have reported that crops such as rice, maize, and leafy vegetables exhibit marked yield reductions when irrigation water salinity exceeds 4–6 dS m^{-1}, depending on crop tolerance and soil properties. Beetroot, with a threshold salinity of ~6 dS m^{-1} [52], could potentially maintain reasonable productivity under moderate salinity; however, sustained exposure to higher ECe levels may lead to ion toxicity, reduced water uptake, and impaired root development.

Further research in the MRD context should therefore explore beetroot responses to moderate and high salinity irrigation ($\geq$2–6 dS m^{-1}), considering interactions between irrigation management, soil ECe accumulation, and local adaptation strategies such as mulching, drainage improvement, or blending of irrigation water sources. Such studies would provide practical guidance for integrating beetroot into saline-affected farming systems across mega deltas experiencing increasing salinity intrusion.

In addition to salinity, alkaline stress is another constraint commonly associated with coastal and deltaic soils, where salinization often occurs in tandem with alkalization. Although salt and alkaline stresses share similar features such as osmotic and ionic imbalances, alkaline conditions introduce additional challenges due to high soil pH, Na^{+} toxicity, and limited nutrient availability. These factors can impair root function and nutrient uptake, ultimately reducing growth and productivity.

Studies on *Beta vulgaris* have shown that the mechanisms conferring salt tolerance may also contribute to its resilience under alkaline stress. Under high-pH conditions, sugar beet plants maintain Na^{+}–K^{+} homeostasis and activate antioxidant enzymes such as catalase (CAT), ascorbate peroxidase (APX), and superoxide dismutase (SOD), which mitigate oxidative damage caused by reactive oxygen species (ROS) [52–54]. Interestingly, mild alkaline conditions (pH 8–9) have been reported to enhance photosynthetic activity, chlorophyll content, and overall growth performance compared with neutral or acidic soils [55]. This suggests that *Beta vulgaris* can adapt to slightly alkaline environments through integrated ionic and antioxidant regulation. Given that parts of the MRD exhibit both mild salinity and alkalinity during the dry season, understanding the combined effects of these stresses is critical for crop diversification. Future studies should therefore investigate beetroot performance under saline–alkaline field conditions to determine its adaptive potential and identify management practices that optimize yield in marginal soils.

4.5. Role of Mulching in Enhancing Irrigation Efficiency. Field results (trial 3) demonstrated that combining mulching with sensor-based irrigation (CI-Mulching) improved soil moisture stability, minimized salt accumulation, and enhanced WUE (Figure 5). This outcome agrees with findings from earlier research showing that straw mulching reduces evaporation losses and contributes to better root zone conditions for crops [5, 56]. The CI-Mulching treatment had the highest yield among all treatments, supporting the hypothesis that integrating water-saving technologies with traditional soil management practices offers synergistic benefits for sustainable crop production [57, 58].

Together, these results provide strong evidence supporting the use of the Chameleon sensor as an effective tool for optimizing irrigation in saline-prone, water-limited environments such as the MRD. Future studies should explore its long-term effects on soil salinity and nutrient leaching, particularly under more extreme salinity levels.

5. Conclusion

This study evaluated the applicability and effectiveness of the Chameleon soil water sensor for managing irrigation in upland crop systems established during the dry season on rice fields in the MRD, Vietnam—an area increasingly

affected by saline intrusion and freshwater scarcity. Through three sequential trials, the sensor was validated across varying soil textures, salinity levels, and cultivation conditions (greenhouse and field), including integration with straw mulching.

Key findings revealed that the Chameleon sensor provided reliable and accurate soil moisture feedback across sand, clay loam, and silty clay soils. In greenhouse experiments, sensor-guided irrigation reduced water use by up to 54% without negatively impacting beetroot growth or yield. Although limited leaching under reduced irrigation slightly increased salt accumulation, the overall salinity levels remained within the crop's tolerance threshold. Field results further demonstrated that combining sensor-based irrigation with straw mulching not only enhanced WUE but also stabilized soil moisture and limited salt accumulation, thereby improving crop performance under saline irrigation conditions.

Collectively, these results support the Chameleon sensor as a practical, low-cost tool for precision irrigation in smallholder settings. Its integration with mulching presents a sustainable strategy for managing salinity and conserving water resources in the MRD. Future work should focus on more potential upland crops in multi-season field validation and long-term assessments of salinity management and farmer adoption in rice-crop rotation systems.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure

The experimental sites across provinces in the Mekong Delta, Vietnam, were determined based on administrative boundaries defined prior to July 01, 2025.

Conflicts of Interest

The authors declare no conflicts of interest.

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