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Performance Evaluation of a Water-Conserving Drip Irrigation System for Sustainable Vegetable Production under Greenhouse Conditions in Ogbomoso, Nigeria

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Abstract

Greenhouse farming offers a controlled environment that promotes precision irrigation and sustainable crop production. However, conventional irrigation practices in water-scarce regions such as Ogbomoso, Nigeria, often result in inefficiencies including evaporation, runoff, and over-irrigation. This study was conducted to evaluate the efficiency of a prototype irrigation system developed to conserve water while maintaining optimal vegetable growth. A dome-shaped 8 × 24 m greenhouse integrated with a drip irrigation system was designed and constructed. The crop water requirement (ETc) was determined using the Blamey–Cradle approach, while three deficit irrigation regimes—100%, 80%, and 60% ETc were examined to assess their effects on plant height, leaf number, and leaf diameter. Similarly, fertilizer rates of 0, 25, 50, and 75 kg/ha were applied to evaluate nutrient response under controlled conditions. Results showed that greenhouse temperatures ranged between 24.6°C and 25.6°C, with corresponding ETc values from 4.24 to 5.56 mm/day. Plant growth parameters under 100%, 80%, and 60% ETc averaged 250.86, 210.74, and 165.28 mm in height; 25, 32, and 11 leaves; and 190.41, 165.79, and 145.62 mm in leaf diameter, respectively. For fertilizer application, plant height, number of leaves, and leaf diameter peaked at 286.98 mm, 34, and 213.26 mm, respectively, under 50 kg/ha. Soil parameters including electrical conductivity, pH, organic matter, and temperature improved under moderate irrigation and fertilizer conditions. Regression models revealed R^2 values of 0.998 and 0.999, confirming strong predictive accuracy. The study concludes that 80% ETc and 25–50 kg/ha fertilizer optimize greenhouse productivity, conserve water, and sustain soil fertility.

Keywords: Greenhouse Farming, Crop Water Requirement, Deficit Irrigation, Fertilizer Rate, Soil Properties

Introduction

Water remains one of the most critical natural resources for agricultural sustainability, serving as a fundamental input for plant growth and food production (Sabir *et al.,* 2024). In recent decades, global agricultural systems have faced unprecedented pressure due to rapid population growth, urban expansion, and the increasing demand for food, all of which have significantly strained available freshwater resources (Wang, 2022). Agriculture currently accounts for nearly 70% of global freshwater withdrawals, highlighting the need for more efficient water management practices to ensure long-term productivity and food security (Muzammal *et al.*, 2024).

Consequently, optimizing water use through innovative agricultural technologies has become central to the global sustainability agenda, particularly in regions where climatic variability and water scarcity pose severe challenges to agricultural resilience (Oiganji *et al.*, 2025). In this context, irrigation remains indispensable for sustaining crop production, especially in semi-arid and arid regions where rainfall is inadequate or erratic. Irrigation supports continuous plant growth by providing a consistent water supply that complements natural precipitation, ensuring reliable yields and food availability (McDermid *et al.*, 2023). However, traditional irrigation systems, such as surface or flood irrigation, are often associated with inefficiencies including

water loss through evaporation, percolation, and runoff, as well as soil salinization and nutrient leaching (Ray and Majumder, 2024). These inefficiencies not only compromise water-use efficiency (WUE) but also accelerate groundwater depletion and environmental degradation. As global water resources become increasingly scarce, there is an urgent need to transition from conventional irrigation methods to precision-based systems that minimize waste and enhance WUE under controlled farming environments (Farhaoui *et al.*, 2025).

Greenhouse farming has emerged as a viable solution to address these challenges by providing a controlled microclimate that enhances productivity while reducing resource wastage (Maraveas *et al.*, 2023). Through the regulation of temperature, humidity, and solar radiation, greenhouse farming allows for continuous crop production independent of seasonal fluctuations. Moreover, the integration of modern irrigation systems such as drip or micro-sprinkler systems enables precise water application directly to the plant root zone, thereby reducing evaporation and promoting optimal water use (Deshpande, *et al.*, 2024). Studies have shown that greenhouse systems can achieve WUE values three to ten times higher than open-field systems due to reduced evapotranspiration and controlled environmental parameters (Rahim *et al.*, 2023). Nonetheless, despite their potential, greenhouses often face the challenge of excessive water consumption when traditional irrigation methods are employed within them, underscoring the importance of adopting water-saving innovations such as automated irrigation control systems and soil-moisture-based scheduling (Alharbi *et al.*, 2024).

Furthermore, as climate change intensifies, unpredictable rainfall patterns and rising temperatures continue to threaten agricultural productivity, particularly in developing regions like Nigeria, where water scarcity and unreliable rainfall severely limit year-round cultivation. Implementing efficient irrigation technologies within greenhouse systems can serve as a practical adaptation measure, enhancing water conservation and ensuring stable food production. The integration of modern techniques such as the Blamey–Cradle approach for estimating crop water requirements and the use of fertigation systems for nutrient management provides an avenue for optimizing both water and nutrient use. Consequently, this study focuses on developing and evaluating a prototype irrigation system designed to minimize water consumption while maintaining optimal crop performance in greenhouse vegetable production. Greenhouse farming uses irrigation water unsustainably, and this reduces environmental quality by depleting freshwater sources, salinizing soil, and causing pollutant runoff that harms surrounding ecosystems. In many greenhouse operations, inefficient irrigation scheduling results in excessive water loss through evaporation and runoff, thereby undermining the core objective of controlled-environment agriculture (Ghiasi *et al.*, 2023).

Additionally, the combined effect of water scarcity and poor water management practices continues to limit agricultural productivity in water-stressed regions, calling for the adoption of technologies that promote efficient water allocation and utilization (Biswas *et al.*, 2025). Consequently, this study is significant as it contributes to addressing global and regional challenges of water scarcity and sustainable agriculture. It provides empirical insights into the performance of a prototype irrigation system designed to optimize WUE in greenhouse vegetable cultivation. The findings are expected to inform policy frameworks, support the adoption of precision irrigation technologies, and guide local farmers toward more sustainable practices that balance productivity with environmental stewardship.

Previous greenhouse irrigation studies have largely focused on comparing conventional methods like drip versus sprinkler systems or evaluating water-use efficiency under fixed irrigation schedules (Ray and Majumder, 2024). However, your work differs by developing and evaluating a prototype irrigation system that integrates the Blamey–Cradle approach for

estimating crop water requirements with fertigation for simultaneous water and nutrient management. Unlike earlier studies that often employed traditional irrigation methods within greenhouses leading to excessive water consumption, evaporation, and runoff (Alharbi *et al*., 2024; Ghiasi *et al*., 2023). This study emphasizes a precision-based, automated system tailored to greenhouse vegetable production. Furthermore, while many previous investigations were conducted in temperate or arid regions with established infrastructure (McDermid *et al*., 2023), your research addresses the specific challenges of Nigeria, where unreliable rainfall, water scarcity, and limited adoption of efficient technologies severely constrain year-round cultivation (Oiganji *et a*l., 2025; Biswas *et al*., 2025). By providing empirical insights into a prototype system that minimizes water depletion, soil salinization, and pollutant runoff, your work directly tackles the unsustainable use of irrigation water in greenhouse, a problem that previous studies have identified but not sufficiently resolved within the context of developing, water-stressed regions like sub-Saharan Africa (Farhaoui *et al*., 2025).

Methodology

Study Area

This study was conducted at the Hydraulic and Greenhouse Research Farm, Department of Civil Engineering, Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria. The area lies within the tropical rainforest belt of West Africa, characterized by bimodal rainfall patterns and a mean annual temperature of approximately 26–34 °C. The region experiences distinct wet and dry seasons, making it suitable for controlled-environment agricultural research such as greenhouse farming.

Greenhouse Design and Construction

A dome-shaped greenhouse structure measuring 8 m × 24 m was designed and constructed to provide a controlled environment for vegetable cultivation to create a longer rectangular footprint for maximum growing space. The greenhouse frame was fabricated from galvanized steel pipes (model: GP 40 mm diameter, manufactured by Dangote Steel Ltd., Nigeria), with the roof and wall coverings made from ultraviolet-stabilized polyethylene film (200 µm thickness, Agriplast India Pvt. Ltd., India). Ventilation was achieved through roof and side vents fitted with insect-proof nylon mesh. The flooring was covered with a 0.1 mm thick polythene mulch sheet to minimize soil moisture loss and weed growth. A drip irrigation system (model: Netafim DripLine 16 mm, Israel) was installed with emitters spaced at 30 cm intervals, each delivering 4 L/h discharge under a working pressure of 1.0 bar because it achieves high water efficiency (90–95%), works seamlessly with the 0.1 mm polythene mulch sheet to suppress weeds and minimize soil moisture loss. The system was connected to a 500 L overhead tank (model: GeePee Tank, Nigeria) supplying irrigation water through a PVC mainline network.

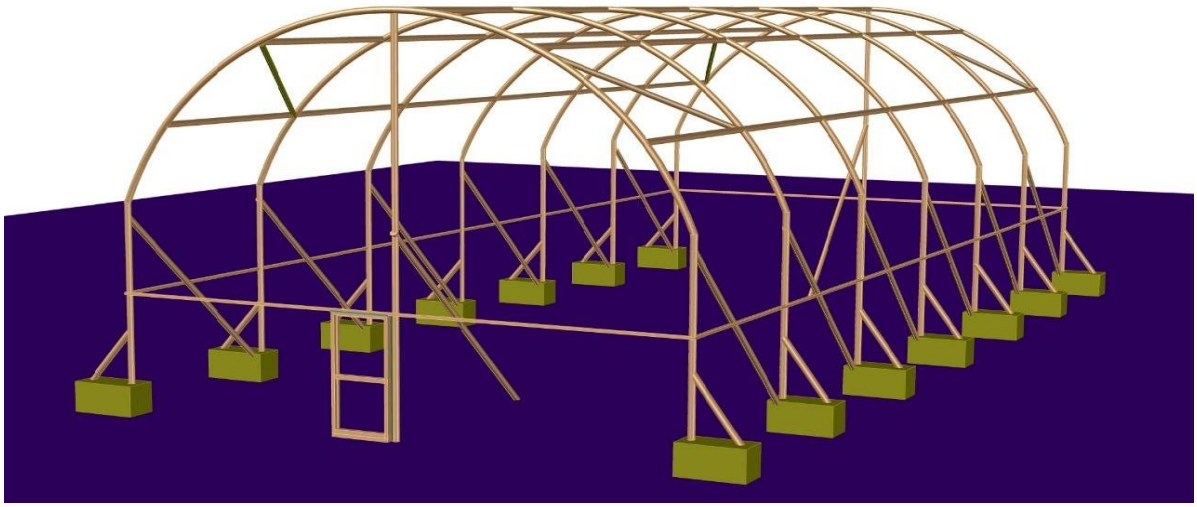

Figure1: The 3D View of the Greenhouse

Crop Establishment and Fertilizer Application

Vegetable were cultivated in planting beds arranged in three irrigation treatment plots of 100%, 80% and 60%. Fertilizer application was carried out using four rate levels: 0, 25, 50, and 75 kg/ha, these rates were selected to represent a control (no fertilizer) and a gradient of low, moderate, and high application rates commonly recommended for leafy vegetable production in similar agro-ecological zones, allowing the identification of an optimal fertilizer rate that maximizes growth without inducing nutrient excess or osmotic stress, applied as NPK 15:15:15 (manufactured by Notore Chemical Industries Plc., Nigeria). The fertilizer was manually broadcast around the root zone two weeks after transplanting and reapplied at nine-week intervals to maintain nutrient uniformity across treatments.

Determination of Crop Water Requirement (ETc)

Crop water requirement (ETc) for the greenhouse vegetables was estimated using the Blamey–Cradle approach, which integrates climatic data and crop coefficients. The equation for ETc is expressed in Equation 1:

$$ETc = Kc \times ETo \quad (1)$$

where *ETc* is the crop evapotranspiration (mm/day), *Kc* is the crop coefficient, and *ETo* is the reference evapotranspiration obtained from climatic data recorded within the greenhouse using a digital weather station Temperature, relative humidity, and solar radiation were automatically logged at 30-minute intervals. The Kc values for each growth stage (initial, mid, and late) were obtained from FAO-56 guidelines for similar leafy vegetables and adjusted for local greenhouse conditions based on observed crop development. The calculated ETc values guided the volume of irrigation water applied under the three deficit irrigation regimes, 100%, 80%, and 60% ETc representing full, moderate, and severe irrigation treatments, respectively. These levels were selected to represent full irrigation, moderate deficit, and severe deficit conditions, respectively, based on commonly used threshold levels in deficit irrigation research that are sufficient to detect significant differences in crop growth and water-use efficiency, whereas intermediate levels such as 70% or 90% ETc were not investigated in order to maintain a manageable experimental design while still capturing a representative range of irrigation regimes from optimal to severely stressed conditions.

The Blaney–Criddle method was selected because it offers a relatively simple, empirically robust approach that relies primarily on temperature and crop coefficient data, making it well

suited for regions such as Ogbomoso where comprehensive meteorological datasets are not readily available, while still providing reasonably accurate ETc estimates for short-cycle vegetable crops under greenhouse conditions. The method assumes that evapotranspiration is primarily a function of mean air temperature and day length, that crop coefficients adequately capture the influence of crop type, growth stage, and ground cover on water use, and that local climatic conditions are reasonably represented by empirically derived adjustment factors. Its main limitations are reduced accuracy in environments with high wind speeds, very low or very high relative humidity, or substantial cloud cover, since it does not directly account for these variables, and it was originally developed for open-field rather than enclosed greenhouse conditions, potentially leading to under- or overestimation of ETc if greenhouse microclimatic factors deviate markedly from the empirical basis of the equation.

Irrigation depths for each treatment were determined by calculating the daily ETc (mm/day) from the climatic data and crop coefficients, converting this to the corresponding volume of water required per plant based on the wetted area and plant spacing, and then applying 100%, 80%, or 60% of this calculated volume according to the assigned deficit irrigation treatment, with irrigation duration adjusted using the known emitter discharge rate to deliver the required depth.

Measurement of Crop Growth Parameters

The effects of the three irrigation regimes on vegetable growth performance were evaluated by measuring plant height, number of leaves, and stem diameter. Measurements were taken weekly for six weeks after transplanting. Plant height was measured using a 1 m graduated ruler (model: Staedtler 561, Germany), leaf count was determined manually, and stem diameter was measured at 5 cm above the soil surface using a digital vernier caliper (model: Mitutoyo 500-196-30, Japan). The average of three plants per treatment was used for analysis.

Soil Sampling and Physico-Chemical Characterization

Soil samples were collected before and after the experiment to assess the temporal changes in physico-chemical properties under different irrigation and fertilizer regimes. Sampling was conducted at a depth of 0–20 cm using a stainless-steel auger (model: AMS 401.19, USA). Samples were air-dried, gently crushed, and sieved through a 2 mm mesh sieve (model: Endecotts Ltd., UK). Soil pH was determined using a digital pH meter (model: Hanna HI98103, Romania) in a 1:2.5 soil–water suspension; electrical conductivity (EC) was measured using a portable EC meter (model: Jenway 4510, UK); and organic matter content was analyzed by the Walkley–Black method using standard laboratory reagents. Soil temperature was measured in situ using a digital soil thermometer (model: Testo 110, Germany).

Data Analysis

Experimental data were subjected to statistical analysis to determine the effects of irrigation deficit and fertilizer rates on both crop and soil parameters. Analysis of variance (ANOVA) was performed using IBM SPSS Statistics (version 26.0, USA) to test for significant differences at the 5% probability level.

Results and Discussion

Estimation of Crop Water Requirement

The results presented in Table 1 describe the temporal variation in climatic and crop water requirement parameters for greenhouse-grown vegetables as determined using the Blamey–Cradle approach. At the initial growth stage (0–7 days), seed germination and cotyledon emergence occurred under a mean temperature of 24.71°C, with maximum and minimum temperatures of 27.43°C and 22.00°C respectively. The potential evapotranspiration (ETo) was

recorded at 5.23 mm day^{-1}, while the crop coefficient (Kc) per week and per growth stage were 0.88 and 0.70 respectively, resulting in a corresponding crop evapotranspiration (ETc) of 4.59 mm day^{-1}. This relatively moderate ETc reflects the early vegetative phase, when water demand is minimal due to the limited leaf area and low transpiration rates. Similarly, Ichi *et al.* (2018) reported that young vegetable seedlings generally exhibit lower evapotranspiration owing to incomplete canopy cover and reduced stomatal conductance.

Subsequently, during the period between the 8th and 21st days, there was a gradual increase in vegetative development as the plants established functional root systems and initiated rapid leaf formation. The mean temperature during this interval ranged from 24.64°C to 24.79°C, while ETo values fluctuated slightly between 5.03 and 5.24 mm day^{-1}. Consequently, ETc increased marginally from 4.24 to 4.32 mm day^{-1}, indicating a progressive rise in water requirement driven by expanding foliage and enhanced physiological activity. In agreement with this observation, Oduor (2024) emphasized that evapotranspiration in leafy vegetables increases proportionally with canopy expansion and root development during the establishment phase. As the growth progressed into the 22–28-day period, a significant intensification in vegetative growth and water utilization was observed. This stage corresponded with the peak of nutrient absorption and physiological activity, as ETo increased to 5.44 mm day^{-1}, while Kc rose to 1.02, leading to the highest ETc value of 5.56 mm day^{-1} within this phase. The mean temperature of 24.86°C provided an optimal thermal environment for photosynthetic efficiency and stomatal functioning, both of which contributed to vigorous plant growth. This finding corroborates the report of Okorie *et al.* (2024), who demonstrated that moderate mean temperatures coupled with adequate soil moisture maximize evapotranspiration and promote enhanced biomass accumulation in leafy vegetables under controlled conditions.

Furthermore, during the mid-growth phase (29–42 days), plants achieved full canopy closure and reached their maximum leaf area index. The mean temperature remained stable, ranging from 24.93°C to 25.07°C, while ETc values varied slightly between 4.90 and 5.08 mm day^{-1}. This relative steadiness in ETc reflects an equilibrium between atmospheric demand and available soil moisture, which typically characterizes the crop's mid-season stage where water use efficiency is optimal. Consistent with this trend, Elshony *et al.* (2025) observed that maintaining uniform temperature and soil moisture conditions during mid-growth enhances physiological stability and ensures sustained photosynthetic performance in leafy vegetable species. In the subsequent growth period (43–63 days), corresponding to the harvesting phase, a marginal increase in temperature was noted, reaching a maximum of 29.20°C and a mean of 25.60°C. The ETo values also rose to 5.54 mm day^{-1}, while ETc fluctuated between 4.99 and 5.48 mm day^{-1}. This sustained level of evapotranspiration indicates that the crop maintained considerable water demand due to continuous transpiration from fully developed foliage. However, a slight decline in Kc values towards the final week (0.95) suggests the commencement of physiological decline as senescence sets in. This observation is in line with the report by Onireti *et al.* (2025), who documented a reduction in Kc values near harvest as growth slows and stomatal regulation becomes more pronounced under higher temperatures and extended photoperiods.

Table 1: Crop Water Requirement (ETc) of Greenhouse-Cultivated Vegetable Determined Using the Blamey–Cradle Approach

Days	T max (°C)	T min (°C)	Mean T (°C)	p (%)	ETo (mm day⁻¹)	Kc per growth	Kc per week	ETc (mm day⁻¹)
0 – 7	27.4	22.0	24.7	0.27	5.23	0.70	0.88	4.59
8 – 14	27.6	21.7	24.6	0.26	5.03	0.70	0.84	4.24
15 – 21	27.7	21.9	24.8	0.27	5.24	0.70	0.83	4.32
22 – 28	27.7	22.0	24.9	0.28	5.44	0.95	1.02	5.56
29 – 35	27.9	22.0	24.9	0.25	4.87	0.95	1.01	4.90
36 – 42	28.1	22.0	25.1	0.26	5.08	0.95	1.00	5.08
43 – 49	28.4	22.0	25.2	0.26	5.10	1.05	0.98	4.99
50 – 56	29.0	22.0	25.5	0.28	5.52	1.05	0.99	5.48
57 – 63	29.2	22.0	25.6	0.28	5.54	0.95	0.95	5.26

T max (°C): *Maximum Temperature,* **T min (°C):** *Minimum Temperature,* **Mean T (°C):** *Average Temperature,* **p (%):** *Relative Humidity,* **ETo (mm day⁻¹):** *Reference Evapotranspiration,* **Kc per growth:** *Crop Coefficient per Growth Stage,* **Kc per week:** *Crop Coefficient per Week,* **ETc (mm day⁻¹):** *Crop Evapotranspiration or Crop Water Requirement*.

Effects of Deficit Irrigation

The results presented in Figure 2 show the variation in plant height of greenhouse-cultivated vegetables under different irrigation levels (100%, 80%, and 60% of crop evapotranspiration, ETc) across the growing period. At the initial growth phase (0–7 DAS), seedlings recorded the lowest mean height, with the fully irrigated treatment (100% ETc) attaining 25.38 mm, while the moderately and severely deficit irrigated treatments (80% and 60% ETc) reached 23.14 mm and 20.42 mm respectively. This initial disparity indicates that adequate soil moisture at the germination stage enhances early seedling vigor and elongation. Similarly, Akintola *et al.* (2025) reported that sufficient moisture availability during emergence significantly promotes cell expansion and turgidity, thereby accelerating initial shoot development in leafy vegetables. As growth advanced into the 8–21 DAS period, a progressive increase in height was observed across all irrigation treatments, reflecting active vegetative development and root establishment. Plant height increased to 80.58 mm in the 100% ETc treatment, while moderate and severe water deficits recorded 72.49 mm and 60.34 mm respectively. The consistent difference among treatments at this stage highlights the importance of optimal irrigation for sustaining leaf expansion and shoot elongation. In agreement with this trend, Chada *et al.* (2023) found that water stress reduces turgor pressure and consequently limits stem elongation due to impaired cell division and nutrient translocation within plant tissues.

Furthermore, during the mid-growth phase (22–35 DAS), which corresponds to the rapid vegetative development stage, plant height increased substantially in all treatments. The fully irrigated plants reached 160.47 mm, compared to 141.38 mm and 115.62 mm under 80% and 60% irrigation levels respectively. This phase coincides with vigorous canopy formation and photosynthetic activity, which are both water-dependent physiological processes. The observed reduction in height under water-deficit conditions suggests that limited moisture availability constrained stomatal conductance and photosynthetic efficiency. A comparable result was reported by Mashamaite *et al.* (2024), who observed that moderate water stress reduces vegetative growth rate and leaf expansion in greenhouse-grown spinach due to restricted carbohydrate synthesis.At the later growth phase (36–49 DAS), the plants attained more pronounced height differences among treatments. The 100% ETc treatment achieved 220.74 mm at 49 DAS, while 80% and 60% ETc recorded 190.56 mm and 150.37 mm respectively. This progressive divergence illustrates the cumulative effect of prolonged moisture deficit on plant morphology. The fully irrigated treatment maintained optimal water supply, ensuring continuous cell expansion and nutrient mobility, whereas water-stressed plants exhibited

reduced elongation rates as a result of osmotic stress and metabolic limitations. Toward the final growth phase (50–63 DAS), the trend of increasing plant height continued, although the rate of increment began to decline as plants approached physiological maturity.

The maximum height of 250.86 mm was recorded under the 100% ETc treatment, while 80% and 60% irrigation levels yielded 210.74 mm and 165.28 mm respectively. The reduction in growth rate towards the end of the growing period could be attributed to a shift in assimilate allocation from vegetative structures to reproductive or storage tissues. However, the consistently higher growth observed under full irrigation demonstrates that water availability remained a critical determinant of final plant stature. This observation is consistent with the findings of Adotey *et al.* (2021), who reported that water-sufficient treatments significantly enhanced final plant height, leaf area index, and overall biomass accumulation compared to water-deficit regimes in controlled greenhouse experiments.

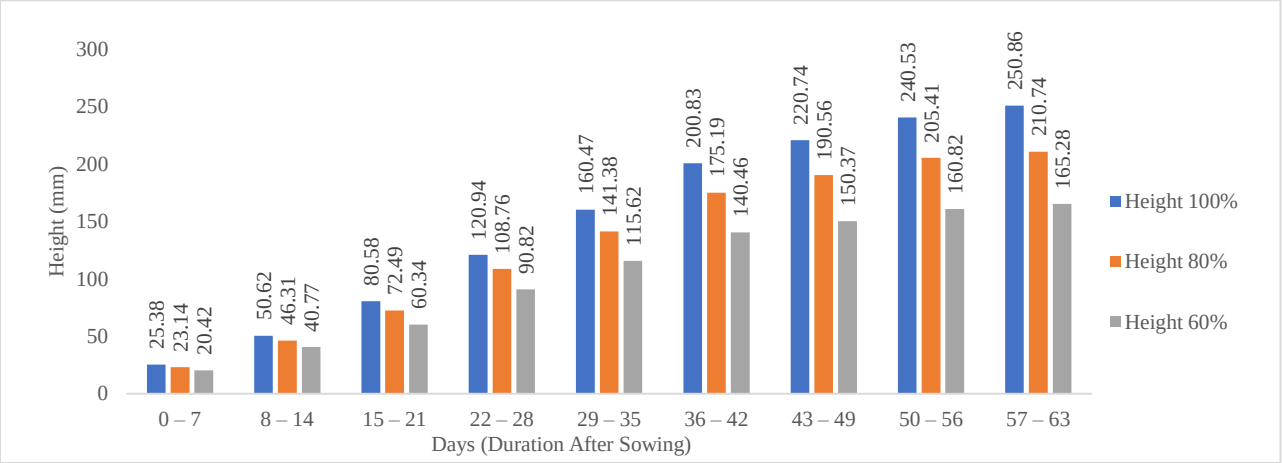

Figure 2: Variation of Plant Height (mm) under Different Irrigation Levels with Days after Sowing (DAS)

The results presented in Figure 3 illustrate the variation in the number of leaves of greenhouse-cultivated vegetables under different irrigation levels (100%, 80%, and 60% of ETc) across the growing period. At the early stage of growth (0–7 DAS), the number of leaves ranged between 2 and 3 across the treatments, with the 80% irrigation level recording a slightly higher leaf count compared to the 100% and 60% treatments. This marginal increase under moderate water deficit may be attributed to a mild physiological stress response that temporarily stimulates leaf initiation during early vegetative establishment. Similarly, Solankey *et al.* (2021) observed that moderate water stress can enhance initial leaf formation in leafy vegetables by promoting adaptive morphological adjustments that optimize light interception. As growth progressed between 8–21 DAS, a steady increase in leaf number was observed across all irrigation levels, reflecting the phase of active leaf development and canopy establishment. The 100% irrigation treatment recorded 9 leaves, while the 80% and 60% treatments had 10 and 7 leaves respectively by 21 DAS. The slight advantage of the 80% treatment at this stage suggests that mild deficit irrigation might improve stomatal efficiency and promote moderate vegetative growth before water limitation becomes physiologically constraining. This finding corresponds with the report of Ukwu *et al.* (2023), who noted that moderate water restriction in greenhouse spinach resulted in increased leaf proliferation due to improved water use efficiency and stomatal regulation during early vegetative stages.

Furthermore, during the mid-growth phase (22–35 DAS), a marked difference in the number of leaves became apparent among treatments. The fully irrigated plants produced 17 leaves,

followed by 20 leaves under 80% irrigation and 13 leaves under 60% irrigation at 35 DAS. This period corresponds to the stage of intense photosynthetic activity, where adequate moisture is essential for sustaining turgor pressure and leaf expansion. The significant reduction observed under severe deficit (60%) may be due to restricted cell division and limited nutrient mobility. In agreement with this observation, Barka *et al.* (2025) reported that water deficiency at mid-growth stages reduces both leaf number and leaf area index due to reduced photosynthate allocation to new foliage. At the later vegetative phase (36–49 DAS), the divergence between treatments became more pronounced, with the 100% ETc treatment recording 23 leaves, 80% irrigation producing 28 leaves, and 60% irrigation falling to 15 leaves. The exceptionally higher leaf count in the 80% treatment may indicate an adaptive compensatory response, where moderate water deficit promotes greater leaf proliferation for efficient light capture under stress conditions. However, prolonged water limitation, as in the 60% treatment, evidently restricted further leaf initiation and expansion. This pattern is comparable to the findings of Okechukwu *et al.* (2021), who demonstrated that slight water stress improved leaf multiplication in greenhouse lettuce, but severe stress significantly reduced total leaf count and canopy spread.

Toward the final growth phase (50–63 DAS), leaf number declined slightly under the fully irrigated condition but continued to increase under moderate deficit irrigation, reaching a peak of 32 leaves under the 80% ETc regime. In contrast, the severely deficit-irrigated plants recorded a sharp decline to 11 leaves, suggesting premature senescence and reduced photosynthetic potential. The reduction in leaf number under severe deficit conditions reflects accelerated leaf abscission, a mechanism plants adopt to minimize transpiration under prolonged stress. This observation agrees with Zikki *et al.* (2020), who noted that sustained water stress induces early senescence and leaf drop in greenhouse-grown leafy vegetables, resulting in diminished canopy size and productivity.

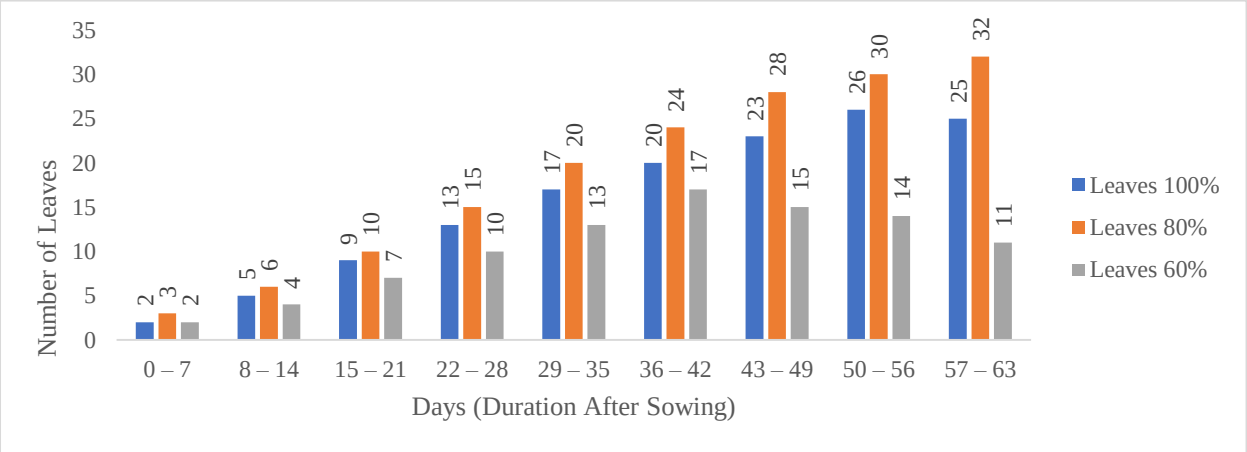

Figure 3: Variation of Number of leaves of Greenhouse-Cultivated Vegetable under Different Irrigation Levels with Days after Sowing (DAS)

The results presented in Figure 4 describe the variation in the leaf diameter of greenhouse-cultivated vegetables under three irrigation regimes (100%, 80%, and 60% of ETc) over the growth period. At the initial growth stage (0–7 DAS), the leaf diameter ranged from 15.38 mm under 60% irrigation to 18.45 mm under full irrigation. The smallest diameter recorded under the 60% regime suggests that early moisture deficiency hindered initial cell expansion and leaf development. This observation aligns with the report of Djanaguiraman *et al.* (2024), who noted that water stress during seedling establishment limits leaf expansion by reducing cell turgidity and meristematic activity. As the plants progressed to 8–14 DAS, leaf diameter increased noticeably across all irrigation levels, reflecting active vegetative growth. The 100%

irrigation treatment recorded the largest diameter of 38.23 mm, followed by 35.19 mm under 80% irrigation and 30.54 mm under 60%. This increase is attributed to adequate water availability facilitating photosynthetic activity and leaf cell enlargement. However, the decline in diameter under deficit conditions indicates the adverse effect of water stress on leaf area development. In a similar study, Seymen *et al.* (2021) found that leaf size in spinach was significantly reduced under deficit irrigation due to decreased water potential and restricted nutrient translocation to expanding tissues.

During the rapid vegetative stage (15–21 DAS), leaf diameter exhibited a sharp increase under optimal irrigation, reaching 95.37 mm at 100% ETc, compared to 85.49 mm and 50.67 mm under 80% and 60% irrigation, respectively. The marked difference between treatments during this phase highlights the sensitivity of leaf expansion to water availability. The extremely low value under the 60% irrigation regime could be linked to reduced stomatal conductance and limited chlorophyll synthesis, both of which impair photosynthetic efficiency. This finding corroborates the results of Fasinmirin *et al.* (2023), who observed a similar pattern in greenhouse-grown amaranthus, where deficit irrigation significantly reduced leaf expansion and overall canopy formation. At the mid-growth stage (22–35 DAS), the diameter values fluctuated slightly, showing a reduction between 22–28 DAS before rising again by 29–35 DAS. The leaf diameter at full irrigation peaked at 130.54 mm, followed by 115.64 mm under 80% and 90.72 mm under 60%. The brief reduction observed at 22–28 DAS may be attributed to energy diversion toward root elongation and canopy densification, which are characteristic of vegetative stabilization. However, the subsequent increase reinforces the importance of sufficient water in maintaining turgidity and cell elasticity.

According to Kongsil *et al.* (2024), fluctuations in leaf diameter at mid-growth can occur due to changing physiological priorities, where plants adjust resource allocation between foliage and roots in response to varying soil moisture levels. In the late vegetative stage (36–49 DAS), a sharp rise in leaf diameter was observed under all treatments, with the maximum value of 225.34 mm recorded under full irrigation. The 80% irrigation level produced a slightly smaller diameter (190.28 mm), while the 60% treatment lagged considerably (130.56 mm). This stage corresponds to the period of maximum canopy expansion and photosynthetic activity, emphasizing the direct influence of water on leaf morphology. The decline observed under the 60% treatment may result from restricted water uptake and nutrient deficiency. This observation agrees with Akintola *et al.* (2025), who reported that insufficient irrigation during the late vegetative phase leads to reduced leaf thickness and limited surface expansion, ultimately lowering photosynthetic efficiency. Toward the end of the growth period (50–63 DAS), leaf diameter showed a declining trend across treatments, especially under 80% and 60% irrigation, suggesting the onset of physiological maturity and partial senescence. The fully irrigated plants maintained a relatively higher diameter, averaging 190.41 mm by 63 DAS, compared to 165.79 mm and 145.62 mm under 80% and 60% irrigation, respectively. The reduction at this stage can be attributed to water redistribution toward reproductive structures and decreased cell division rates. In consonance with this result, Esan *et al.* (2023) observed that leaf shrinkage during late growth stages is a normal physiological response to aging and reduced water absorption efficiency in the root system.

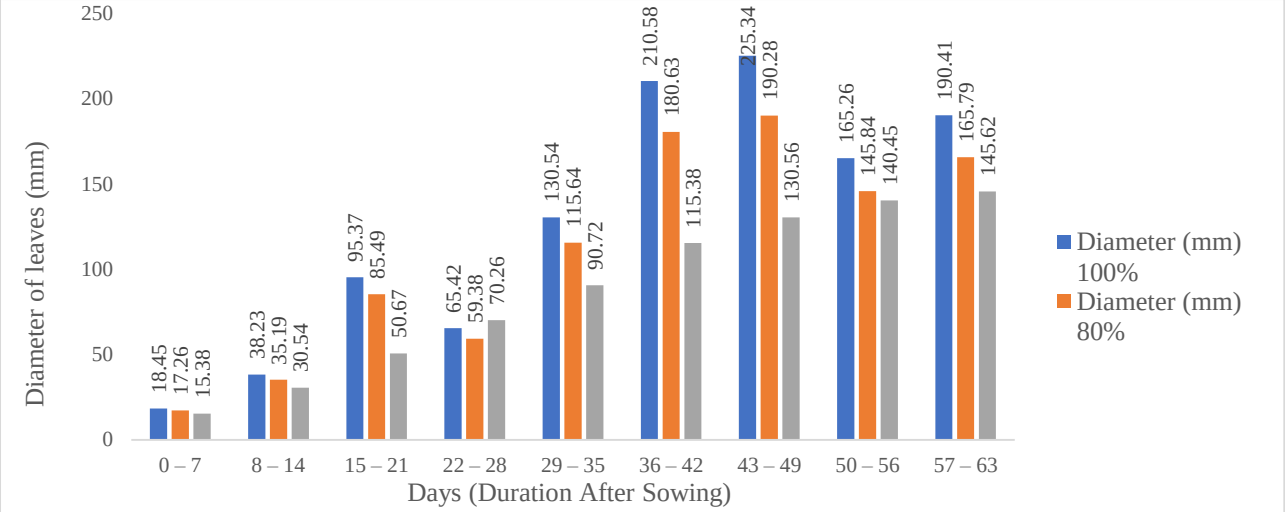

Figure 4: Variation of Diameter of Leaves of Greenhouse-Cultivated Vegetable under Different Irrigation Levels with Days after Sowing (DAS)

Impact of Fertilizer Rate

The results presented in Table 2 illustrate the variation in plant height of greenhouse-cultivated vegetables under different fertilizer application rates (0, 25, 50, and 75 mg/a) throughout the growth period. At the early growth stage (0–7 DAS), plant height ranged from 25.38 cm in the control (0 mg/a) to 28.95 cm under 50 mg/a fertilizer application, with a slight reduction to 27.92 cm under 75 mg/a. The increase in plant height with fertilizer application at this stage reflects the positive influence of nitrogen and other macronutrients on early vegetative development. The slight decline at the highest fertilizer level may be attributed to initial osmotic stress caused by excess nutrient concentration in the root zone. According to Israel *et al.* (2022), moderate fertilizer doses promote early seedling vigor, while excessive application can suppress root elongation due to increased soil salinity or nutrient imbalance. During the subsequent stage (8–14 DAS), a consistent rise in height was observed across all treatments, with values ranging from 50.62 cm in the control to 57.71 cm at 50 mg/a. The plants treated with 25 mg/a showed moderate growth (53.64 cm), while those with 75 mg/a recorded a slightly lower height (55.68 cm) compared to 50 mg/a. This trend suggests that the 50 mg/a application rate provided the most favorable nutrient balance for vegetative expansion. Adequate nitrogen supply at this stage enhances chlorophyll synthesis and photosynthetic efficiency, thereby promoting rapid stem elongation.

This finding aligns with the report of Adekola *et al.* (2020), who observed that moderate fertilization in leafy vegetables resulted in optimal vegetative growth and improved canopy development compared to both under- and over-fertilized treatments. At the active vegetative phase (15–28 DAS), plant height increased significantly under all fertilizer treatments. Between 15–21 DAS, plants treated with 50 mg/a attained a height of 91.46 cm, exceeding the control (80.58 cm) by approximately 13.5%. Similarly, during 22–28 DAS, the same treatment reached 137.89 cm, while the control and 75 mg/a treatments recorded 120.94 cm and 133.03 cm respectively. The superior performance at 50 mg/a highlights its efficiency in supplying essential nutrients, particularly nitrogen and phosphorus, which stimulate stem elongation and leaf expansion. The slight decline at 75 mg/a supports the view that excessive fertilizer application may inhibit nutrient uptake efficiency due to ionic competition or increased soil osmotic potential. This outcome is comparable to the findings of Adelere *et al.* (2022), who reported that intermediate fertilizer doses yielded higher plant height and biomass in amaranth compared to both low and high nutrient levels. As the plants approached the mid-growth stage (29–42 DAS), rapid height increment continued, with the 50 mg/a treatment consistently

outperforming others. At 36–42 DAS, plant height reached 235 cm under 50 mg/a, followed by 226.08 cm under 75 mg/a, and 212.88 cm under 25 mg/a. The control recorded the least growth (200.83 cm). The pronounced difference among treatments during this phase indicates the sustained influence of nutrient availability on cell elongation and photosynthetic efficiency.

Fertilizer application enhances the synthesis of growth hormones such as auxins and gibberellins, which promote stem elongation. In agreement, Ojeniyi *et al.* (2024) emphasized that balanced fertilizer application during vegetative development maintains optimal nutrient uptake and accelerates morphological growth in leafy vegetables. In the late vegetative phase (43–56 DAS), the plants attained their peak height values, reflecting the culmination of active vegetative growth. The 50 mg/a treatment achieved the maximum height of 274.21 cm at 50–56 DAS, compared to 264.67 cm under 75 mg/a and 255.16 cm under 25 mg/a, while the control remained at 240.53 cm. This result reinforces the earlier observation that 50 mg/a represents the optimal rate for maximizing vegetative performance without inducing nutrient stress. The slight reduction in height at higher fertilizer levels may also be linked to excessive nitrogen promoting soft, succulent tissues, which are more prone to lodging and less efficient in sustaining further growth. This observation is consistent with Igwe and Obalum (2022), who reported that excessive nitrogen application leads to luxuriant but unstable vegetative growth, negatively impacting structural rigidity and long-term productivity.

Toward the end of the growth period (57–63 DAS), growth rates began to stabilize, with minor increases observed across all treatments. The plants under 50 mg/a reached a final mean height of 286.98 cm, indicating superior growth sustainability compared to other treatments. This trend demonstrates that nutrient availability at moderate levels supports both early and sustained vegetative growth. According to Ahmed *et al.* (2023), maintaining optimal fertilizer rates ensures a continuous nutrient supply for both leaf and stem development, thereby promoting high-quality biomass accumulation without causing physiological stress. The results presented in Table 3 show the variation in the number of leaves per plant of greenhouse-cultivated vegetables under different fertilizer application rates (0, 25, 50, and 75 mg/a) throughout the growth period. At the early stage (0–7 DAS), leaf emergence was relatively low across all treatments. Plants supplied with 50 mg/a fertilizer produced four leaves, while those under 0, 25, and 75 mg/a recorded two, three, and three leaves respectively. This indicates that moderate fertilizer application enhanced early leaf initiation due to improved nutrient availability that stimulated photosynthetic activity and cell differentiation. Similarly, Israel *et al.* (2022) observed that moderate nutrient input enhances seedling establishment and leaf initiation, while excessive fertilizer can hinder early growth due to ionic stress in the root zone.

Table 2: Plant height (cm) at different fertilizer rates

Days (Duration After Sowing)	0 mg/a	25 mg/a	50 mg/a	75 mg/a
0–7	25.38	26.9	28.95	27.92
8–14	50.62	53.64	57.71	55.68
15–21	80.58	85.42	91.46	88.64
22–28	120.94	128.4	137.89	133.03
29–35	160.47	170.28	182.95	176.52
36–42	200.83	212.88	235	226.08
43–49	220.74	233.97	251.62	242.81
50–56	240.53	255.16	274.21	264.67
57–63	250.86	266.92	286.98	277.21

Furthermore, during the 8–14 DAS period, leaf production increased steadily under all fertilizer rates, with plants treated with 50 mg/a producing eight leaves compared to seven, six, and five under 75, 25, and 0 mg/a respectively. This trend signifies that moderate fertilization improves

nitrogen uptake, which in turn promotes chlorophyll synthesis and leaf tissue expansion. The slightly reduced leaf number at 75 mg/a may be attributed to nutrient imbalance that limits physiological efficiency. Moreover, Otie *et al.* (2021) reported that optimal nitrogen concentration stimulates photosynthetic activity, resulting in higher leaf formation, whereas excessive supply suppresses vegetative growth due to osmotic stress. Additionally, between 15–28 DAS, there was a pronounced increase in leaf number as plants entered the active vegetative phase. At 15–21 DAS, the 50 mg/a treatment recorded 13 leaves per plant, while the control had only nine. Similarly, at 22–28 DAS, plants under 50 mg/a produced 18 leaves compared to 16, 15, and 13 under 75, 25, and 0 mg/a respectively. The rapid increase in leaf number indicates that the 50 mg/a rate supplied adequate nutrients for accelerated vegetative growth. In agreement, Simiyu *et al.* (2023) found that moderate fertilizer application promotes efficient nutrient utilization, leading to enhanced leaf expansion and canopy development during the mid-growth stage of vegetables.

Moreover, as the plants approached 29–42 DAS, a remarkable increase in leaf production was observed across all treatments, with the 50 mg/a application maintaining the highest performance. At 29–35 DAS, plants under this treatment recorded 23 leaves, increasing to 27 leaves at 36–42 DAS. In contrast, the control produced only 17 and 20 leaves during the same periods. This outcome highlights the role of sufficient fertilization in enhancing photosynthetic efficiency and sustained leaf proliferation. Similarly, Ajayi *et al.* (2022) reported that vegetables supplied with moderate nitrogen and phosphorus exhibited improved leaf area and chlorophyll accumulation, thereby achieving a higher rate of vegetative expansion compared to nutrient-deficient conditions.

Table 3: Number of leaves per plant at different fertilizer rates

Days (Duration after Sowing)	0 mg/a	25 mg/a	50 mg/a	75 mg/a
0–7	2	3	4	3
8–14	5	6	8	7
15–21	9	11	13	12
22–28	13	15	18	16
29–35	17	20	23	21
36–42	20	24	27	25
43–49	23	28	32	29
50–56	26	31	35	32
57–63	25	30	34	31

Furthermore, during the 43–56 DAS phase, which represents the peak vegetative period, the number of leaves continued to increase significantly. The 50 mg/a treatment reached 32 and 35 leaves at 43–49 and 50–56 DAS respectively, while the control maintained lower values of 23 and 26 leaves. Although the 75 mg/a treatment produced more leaves than the control, it slightly underperformed compared to the 50 mg/a rate, suggesting that nutrient excess can limit physiological efficiency due to root-zone salinity. In consonance, Saha *et al.* (2023) reported that excessive fertilization can induce metabolic imbalance, while moderate levels sustain continuous leaf formation and delay senescence in leafy vegetables.

Additionally, towards the end of the growth period (57–63 DAS), a slight reduction in leaf number was recorded across all treatments, which may be linked to natural senescence and leaf drop. Nonetheless, plants under 50 mg/a still maintained the highest leaf number (34), compared to 31, 30, and 25 recorded under 75, 25, and 0 mg/a respectively. This result suggests that moderate fertilizer application sustains leaf vitality and photosynthetic activity even as plants approach maturity. Similarly, Mesele and Huising (2025) reported that optimal nutrient

management delays leaf aging, ensuring prolonged photosynthetic efficiency during the late vegetative phase of crop growth.

The results presented in Table 4 illustrate the variation in leaf diameter (mm) of greenhouse-cultivated vegetables under different fertilizer application rates at 0, 25, 50, and 75 mg/a over the 63-day growth period. At the initial stage (0–7 DAS), plants treated with 25 mg/a exhibited the highest leaf diameter of 20.64 mm, followed closely by 50 mg/a with 20.09 mm, while the control and 75 mg/a treatments recorded 18.45 mm and 19.37 mm respectively. This early response indicates that a moderate fertilizer dose enhances cell expansion and leaf turgidity, which supports faster early growth. Similarly, Afolabi *et al.* (2024) observed that moderate nitrogen availability during the early vegetative phase improves leaf expansion due to increased chlorophyll synthesis and water retention, unlike both deficient and excessive nutrient conditions which retard early leaf development.

Furthermore, during 8–14 DAS, a progressive increase in leaf diameter was recorded across all treatments. The 25 mg/a fertilizer rate maintained the highest mean leaf diameter of 42.82 mm, while 50 mg/a and 75 mg/a recorded slightly lower values of 41.63 mm and 40.14 mm respectively. The control treatment produced the least value of 38.23 mm, confirming the significance of fertilizer application for leaf structural growth. The slightly higher value under 25 mg/a compared to 50 mg/a may be attributed to early nutrient availability and better osmotic balance, which enhances mesophyll expansion. Moreover, Khoza *et al.* (2025) reported that appropriate nutrient supply, particularly nitrogen and potassium, promotes efficient water absorption and cell enlargement, thereby increasing leaf thickness and surface area during early plant growth.

Additionally, between 15–21 DAS, the leaf diameter increased remarkably across all treatments, reaching 106.82 mm at 25 mg/a and 103.77 mm at 50 mg/a, while the control recorded a significantly lower diameter of 95.37 mm. This increase coincides with the rapid vegetative development stage, during which leaf tissue undergoes active differentiation and expansion. The improvement in diameter under moderate fertilizer rates reflects balanced nutrient uptake that supports vigorous vegetative metabolism. Moreover, during the 22–28 DAS period, a temporary decline in leaf diameter was observed across all treatments, with values decreasing slightly compared to the preceding phase. The reduction could be linked to energy diversion from vegetative growth to root strengthening and canopy establishment. However, the 25 mg/a and 50 mg/a treatments still maintained larger diameters of 73.27 mm and 71.31 mm respectively compared to the control (65.42 mm). This trend implies that nutrient application continues to enhance structural stability and resilience even during transient physiological adjustments. In line with this, Ofoso, (2021) noted that temporary dips in leaf size can occur during canopy reallocation, but moderate fertilization ensures quicker recovery in subsequent growth phases.

Table 4: Diameter of leaves (mm) at different fertilizer rates

Days (Duration After Sowing)	0 mg/a	25 mg/a	50 mg/a	75 mg/a
0–7	18.45	20.64	20.09	19.37
8–14	38.23	42.82	41.63	40.14
15–21	95.37	106.82	103.77	100.14
22–28	65.42	73.27	71.31	68.69
29–35	130.54	146.21	142.18	137.07
36–42	210.58	235.87	229.32	221.11
43–49	225.34	252.27	245.47	236.61
50–56	165.26	185.1	180.76	173.52
57–63	190.41	213.26	208.05	199.93

Furthermore, from 29–42 DAS, there was a significant resurgence in leaf diameter as plants entered peak vegetative activity. The 25 mg/a and 50 mg/a treatments reached diameters of 146.21 mm and 142.18 mm at 29–35 DAS, increasing to 235.87 mm and 229.32 mm at 36–42 DAS, respectively. The control and 75 mg/a treatments recorded noticeably lower values, indicating that nutrient excess or deficiency can both limit physiological efficiency. This period marks maximum photosynthetic efficiency and leaf area development. Similarly, Usman *et al.*, (2024) reported that optimal fertilizer application enhances leaf blade thickness and cell wall expansion, resulting in improved photosynthetic surface and plant vigor. Additionally, between 43–49 DAS, the plants achieved their maximum recorded leaf diameters, with 25 mg/a producing 252.27 mm and 50 mg/a yielding 245.47 mm. Although 75 mg/a also performed better than the control, its leaf diameter (236.61 mm) was slightly lower than the optimum range, suggesting possible nutrient oversaturation that restricts water absorption and cellular enlargement. In agreement, Abdullahi (2024) emphasized that nutrient excess may lead to osmotic stress, thereby slightly suppressing leaf expansion and transpiration efficiency during peak vegetative growth.

Moreover, during the 50–63 DAS period, a decline in leaf diameter was observed in all treatments, possibly due to physiological aging and the onset of reproductive transition. Nevertheless, plants under 25 mg/a and 50 mg/a maintained relatively higher diameters (185.1–213.26 mm and 180.76–208.05 mm respectively) compared to the control (165.26–190.41 mm). The consistent superiority of these treatments suggests that moderate fertilization promotes sustained cell turgor and delayed senescence. Similarly, Babatunde (2022) reported that balanced nutrient management extends the vegetative lifespan of leafy crops by maintaining optimal chlorophyll concentration and tissue elasticity.

Analysis of Soil Property

The results presented in Table 5 reveal the combined effects of fertilizer rates and deficit irrigation regimes on the soil physico-chemical properties, including electrical conductivity (EC), pH, organic matter content, and soil temperature. These parameters are essential indicators of soil fertility and environmental conditions influencing plant growth. At 0 mg/a (control), the EC increased slightly from 0.31 dS/m under full irrigation (100%) to 0.37 dS/m under the most severe water deficit (60%). This increase suggests that limited irrigation led to the accumulation of soluble salts due to reduced leaching. Similarly, Mc Lean, (2020) observed that deficit irrigation promotes salt concentration in the root zone as water evaporates faster than salts are transported downward, thereby elevating soil EC values.

Furthermore, the EC values progressively increased with higher fertilizer rates across all irrigation levels. At 75 mg/a, EC ranged from 0.73 dS/m under 100% irrigation to 0.83 dS/m under 60% irrigation. This consistent increase demonstrates that higher fertilizer application elevates ion concentration in the soil solution, particularly under limited water availability. In agreement, Galal and Soliman (2024) reported that excessive fertilizer input intensifies soil salinity due to nutrient accumulation and reduced percolation under water-deficit conditions, which can negatively affect plant root uptake efficiency.

Moreover, the soil pH exhibited a gradual decline with both increasing fertilizer rate and irrigation deficit. Under 100% irrigation, pH decreased from 6.73 in the control to 6.58 at 75 mg/a, while under 60% irrigation, it further dropped from 6.68 to 6.53. This downward trend implies that nutrient addition, particularly nitrogen-based fertilizers, promotes slight soil acidification through nitrification and hydrogen ion release. Similarly, Paramisparam *et al.* (2021) noted that continuous fertilizer application tends to acidify soils due to the production

of acidic by-products during nutrient transformation, particularly under restricted moisture conditions where buffering capacity is reduced.

Additionally, the organic matter content displayed a marginal but consistent reduction with increasing irrigation deficit. At 100% irrigation, organic matter ranged between 2.46% and 2.52%, while under 60%, it declined slightly to between 2.41% and 2.47%. The minor decrease indicates that reduced irrigation limits microbial decomposition and organic matter mineralization, thereby slowing down nutrient cycling. However, fertilizer application helped to maintain relatively stable organic matter levels across treatments. Furthermore, soil temperature increased progressively with increasing irrigation deficit, rising from 24.27°C under 100% irrigation in the control to 25.56°C under 60%. A similar pattern was observed across all fertilizer treatments, with the highest temperatures recorded under 60% irrigation (26.14°C at 75 mg/a). The rise in temperature under water stress conditions can be attributed to reduced soil moisture, which decreases evaporative cooling. In agreement, da Silva Barros *et al.* (2024) observed that soil temperature tends to rise in deficit-irrigated systems due to reduced soil moisture content and increased exposure to solar radiation, which accelerates heat absorption in the upper soil layers.

Table 5: Effect of Fertilizer Rates and Deficit Irrigation Regimes on Soil Physico-Chemical Properties

Fertilizer rates/ Irrigation	**Electrical conductivity (EC, dS/m)**			**pH**			**Organic matter (%)**			**temperature (°C)**		
Deficit	100%	80%	60%	100%	80%	60%	100%	80%	60%	100%	80%	60%
0 mg/a	0.31	0.33	0.37	6.73	6.71	6.68	2.46	2.43	2.41	24.27	24.91	25.56
25 mg/a	0.45	0.48	0.53	6.68	6.66	6.63	2.49	2.46	2.44	24.65	25.29	25.94
50 mg/a	0.60	0.63	0.68	6.63	6.61	6.58	2.52	2.49	2.47	25.03	25.68	26.32
75 mg/a	0.73	0.77	0.83	6.58	6.56	6.53	2.51	2.48	2.46	24.86	25.50	26.14

Statistical Analysis

The regression analysis presented in Tables 6a and 6b provides a comprehensive assessment of the relationships between fertilizer rate, irrigation deficit, and key soil physico-chemical parameters, namely electrical conductivity (EC), pH, organic matter (OM), and temperature. The results demonstrate the statistical robustness and predictive reliability of both models in explaining the variations in soil behavior under different irrigation and fertilizer management regimes.

From Table 6, the model summaries reveal extremely high correlation coefficients (R = 0.999) for both fertilizer rate and irrigation deficit, signifying near-perfect linear relationships between the independent and dependent variables. The coefficients of determination (R^2 = 0.998 for fertilizer rate and 0.999 for irrigation deficit) indicate that over 99% of the variation in soil properties is explained by the respective models. Corresponding adjusted R^2 values of 0.996 and 0.998 confirm the models' strong explanatory power after accounting for the number of predictors. The standard error of estimate was lower in the irrigation deficit model (0.703) compared to the fertilizer rate model (1.768), suggesting higher predictive precision. Furthermore, the F-change values of 748.187 and 1616.449, both significant at $p < 0.001$, confirm that the regression models are statistically valid and reliable in explaining soil response to applied treatments.

The ANOVA results in Table 7 reinforce these findings. For the fertilizer rate model, the regression sum of squares (9353.123) far exceeded the residual sum of squares (21.877), implying that nearly all variations in the dependent variable are explained by the fertilizer rate.

Similarly, the irrigation deficit model exhibited a regression sum of squares of 3196.539 compared to a minimal residual of 3.461, producing a highly significant F-value of 1616.449 ($p < 0.001$). These results affirm that irrigation deficit contributes more strongly to changes in soil properties than fertilizer rate, highlighting the dominant role of water management in soil performance under greenhouse conditions.

Table 6: Comparative Regression Model Summary for Fertilizer Rate and Irrigation Deficit Models.

Model	R	R Square	Adjusted R Square	Std. Error of Estimate	R Square Change	F Change	df1	df2	Sig. F Change
Fertilizer Rate(kg/a)	0.999	0.998	0.996	1.768	0.998	748.187	4	7	0
Irrigation Deficit (%)	0.999	0.999	0.998	0.703	0.999	1616.449	4	7	0

Table 7: Comparative ANOVA Summary for Fertilizer Rate and Irrigation Deficit Models.

Model	Source	Sum of Squares	df	Mean Square	F	Sig.
Fertilizer Rate(kg/a)	Regression	9353.123	4	2338.281	748.187	0
	Residual	21.877	7	3.125		
	Total	9375	11			
Irrigation Deficit (%)	Regression	3196.539	4	799.135	1616.449	0
	Residual	3.461	7	0.494		
	Total	3200	11			

The regression coefficients summarized in Table 8 further elucidate the direction and strength of these relationships. In the fertilizer rate model, electrical conductivity displayed a positive standardized coefficient ($\beta = 0.691$), implying that higher EC values correspond to increased soil response, though the effect was not statistically significant ($p = 0.178$). Soil pH showed a negative influence ($\beta = -0.352$, $p = 0.475$), suggesting that increasing alkalinity slightly reduces the dependent variable. Organic matter ($\beta = 0.111$, $p = 0.095$) exhibited a marginally significant positive relationship, indicating its moderate contribution to soil productivity. Conversely, temperature showed a significant negative effect ($\beta = -0.205$, $t = -3.731$, $p = 0.007$), confirming that elevated soil temperature reduces soil quality, especially under higher fertilizer applications.

In the irrigation deficit model, organic matter presented the most significant effect ($\beta = 0.470$, $t = 12.063$, $p < 0.001$), demonstrating its crucial role in sustaining soil health under reduced irrigation. Temperature again exhibited a strong inverse and significant influence ($\beta = -0.687$, $t = -18.381$, $p < 0.001$), reinforcing its negative impact on soil behavior during moisture stress.

Table 8: Comparative Coefficients Summary for Fertilizer Rate and Irrigation Deficit Models

Model	Variable	Unstandardized Coefficients (B)	Std. Error	Standardized Coefficients	t	Sig.	Tolerance	VIF
Fertilizer Rate(kg/a)	(Constant)	1062.381	1441.6		0.737	0.485		
	Electrical Conductivity (dS/m)	115.214	76.881	0.691	1.499	0.178	0.002	638.67

	pH	-165.021	218.62	-0.352	-0.755	0.475	0.002	651.00
	Organic Matter (%)	100.446	52.025	0.111	1.931	0.095	0.102	9.844
	Temperature (°C)	-9.582	2.568	-0.205	-3.731	0.007	0.111	9.041
Irrigation Deficit (%)	(Constant)	-967.454	573.4		-1.687	0.135		
	Electrical Conductivity (dS/m)	41.981	30.578	0.431	1.373	0.212	0.002	638.671
	pH	133.262	86.954	0.486	1.533	0.169	0.002	651.009
	Organic Matter (%)	249.596	20.692	0.47	12.063	0	0.102	9.844
	Temperature (°C)	-18.775	1.021	-0.687	-18.381	0	0.111	9.041

The collinearity diagnostics in Table 9 reveal high condition indices (>8900) and variance proportions (>0.65) among the soil parameters, confirming severe multicollinearity, particularly between EC and pH (VIF > 600). This interdependence reflects natural soil processes where ionic balance and temperature interactively regulate nutrient mobility and organic matter decomposition. Although multicollinearity may obscure the distinct effect of individual predictors, the overall model stability remains strong.

Table 9: Comparative Collinearity Diagnostics Summary for Fertilizer Rate and Irrigation Deficit Models

Model	Eigen value	Condition Index	Variance Proportions	Electrical Conductivity	pH	Organic Matter	Temperature
Fertilizer Rate(kg/a)	4.934	1	0	0	0	0	0
	0.066	8.647	0	0	0	0	0
	0	106.841	0	0	0	0.01	0.1
	2.21E-05	472.886	0	0.01	0	0.34	0.24
	6.21E-08	8910.242	1	0.99	1	0.65	0.66
Irrigation Deficit (%)	4.934	1	0	0	0	0	0
	0.066	8.647	0	0	0	0	0
	0	106.841	0	0	0	0.01	0.1
	2.21E-05	472.886	0	0.01	0	0.34	0.24
	6.21E-08	8910.242	1	0.99	1	0.65	0.66

Conclusion

This study concludes that precise irrigation and fertilizer management are essential for optimizing greenhouse vegetable production. The Blamey–Cradle method confirmed a favorable microclimate with a mean temperature of 25.03°C and revealed that irrigation efficiency varies with crop growth stages. Moderate irrigation at 80% ETc and fertilizer rates between 25–50 kg/ha improved plant growth, soil balance, and water-use efficiency. Plant growth decreased at 60% ETc because this irrigation level represents severe water deficit, which induces drought stress in the vegetable crops. Deficit irrigation reduces leaching of salts from the root zone, while high fertilizer application adds more salts, both leading to salt accumulation. Other possible changes include reduced soil moisture content or altered pH, but salinity is the most commonly reported soil property affected by both irrigation and fertilizer management in greenhouse studies.It is recommended that irrigation scheduling follow ETc variations, adopting 80% ETc with 25–50 kg/ha fertilizer, supported by soil testing and automated sensors for sustainable water and nutrient management in greenhouse cultivation.

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