LAUTECH Journal of Civil and Environmental Studies
Volume XVI, Issue II; June, 2026
DOI: 10.36108/laujoces/6202.61.0290

Design and Construction of Suitable Drip Irrigation System for Tomato Cultivation in Greenhouse Farming

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Abstract
Agriculture remains central to ensuring food security globally, yet it faces growing challenges from climate change, water scarcity, and rapid population growth. Consequently, enhancing productivity while conserving water is crucial. This study aims to design and construct a greenhouse drip irrigation system to improve water use efficiency. A 20 × 30 m dome-shaped greenhouse integrated with a drip irrigation system was designed and constructed. Levelling and spot height were conducted using the reduced level method. Soil geotechnical properties were analysed for permeability, bulk density, organic content, and loss on ignition. The system's performance was evaluated under 100%, 80%, and 60% ETc irrigation regimes, and their effects on tomato growth parameters were assessed. The soil analysis recorded average values of bulk density, permeability, loss on ignition and natural moisture content were 1.85 g/cm³, 1.15 × 10^{-4} cm/s, 2.45% and 8.8% respectively. The levelling survey showed a gentle gradient with reduced levels between 101.000 m and 100.165 m. Hydraulic performance yielded total flow rates of 500, 410, and 305 L/h at 100%, 80%, and 60% ETc regimes, respectively. Corresponding efficiencies were 91%, 90.1%, and 88.6%. Final plant heights reached 171, 143.9, and 114.2 cm; leaf counts were 46, 39, and 28; while yields attained 262.8, 310.4, and 186.1 g/ plant for the respective regimes. The results conclude that the 80% ETc irrigation regime achieved the best balance between tomato yield and water use efficiency, demonstrating the sustainability of moderate deficit irrigation for greenhouse production. It is therefore recommended that greenhouse drip irrigation systems adopt 80% ETc as the optimal irrigation schedule to maximize productivity while conserving water resources.

Keywords: Drip irrigation, greenhouse production, water use efficiency, deficit irrigation, evapotranspiration (ETc), food security, water scarcity

Introduction
Agriculture remains central to ensuring food security globally, yet it faces growing challenges from climate change, water scarcity, and rapid population growth (Saleem *et al*., 2025). Consequently, there is a critical need to increase agricultural productivity through more efficient an Irrigation scheduling sustainable methods (Rasyid and Ningsih, 2024). Greenhouse farming has emerged as a viable solution, providing a controlled environment that optimizes factors such as temperature, humidity, and irrigation to ensure higher and more consistent yields throughout the year (Maraveas and Bartzanas, 2023). Unlike traditional open-field systems, greenhouses significantly reduce exposure to harsh climatic conditions and improve resource utilization, representing a modern approach to sustainable crop production (Argent *et al*., 2024).

Efficient irrigation remains one of the most vital components of greenhouse farming, as water mismanagement can limit both yield and sustainability (Ray and Majumder, 2024). Traditional irrigation systems such as sprinklers and surface methods often result in excessive water loss and uneven distribution, leading to poor water use efficiency (Lakhiar *et al*., 2024). In contrast, drip irrigation by delivering water directly to the root zone ensures minimal losses from evaporation and runoff while maintaining optimal soil moisture levels (Kumar *et al*., 2024).

Furthermore, modern drip irrigation systems now integrate advanced technologies such as automated controls and fertigation units, allowing precise water and nutrient application (Sarma *et al*., 2023). Despite these advancements, many farmers have not adopted such systems due to high setup costs, limited technical knowledge, and the absence of site-specific design standards (Mizik, 2023). The advantages of drip irrigation in greenhouse farming are far-reaching (Yang *et al*., 2023). It enhances water use efficiency, minimizes fertilizer losses, and promotes healthier plant growth while conserving limited water resources (Yang *et al*., 2024). The incorporation of IoT-based sensors and automated scheduling further improves real-time control and ensures that plants receive water according to their growth stage and environmental conditions (Rahman *et al*., 2024). Therefore, designing a suitable drip irrigation system that is both cost-effective and efficient is essential to achieving sustainable agricultural intensification.

However, a major problem persists as many greenhouse farms still rely on inefficient irrigation methods that waste water and energy (Ungureanu *et al*., 2020). Poor design features, such as non-uniform emitter distribution and lack of pressure regulation, further reduce irrigation performance and crop yield (Yang *et al*., 2025). These challenges highlight the need for developing adaptable, well-designed drip irrigation systems suited to different greenhouse environments. This study is therefore significant because it provides a practical framework for designing and constructing an efficient greenhouse drip irrigation system that promotes water conservation and enhances crop productivity.

Materials and Method

Brief Description of the Study Area

The study was conducted at the Greenhouse Unit of Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria, situated at latitude 8.1333° N and longitude 4.2667° E. The greenhouse measured 20 m × 30 m, giving a total floor area of 600 m². The greenhouse drip irrigation system was designed based on a net irrigation requirement of 36.58 mm, a gross irrigation requirement of 56.28 mm, and an irrigation interval of five days (Zhang *et al*., 2025). The irrigation time per event was determined to be approximately 1.05 hours for tomato crops.

Materials and Equipment

The primary materials used for the design and construction of the drip irrigation system included PVC pipes (32 mm mainline, 25 mm sub-main, and 16 mm laterals) manufactured by Flow-Guard, USA; emitters with a discharge rate of 2 L/hr (Netafim, Israel); and various control fittings such as filters, pressure regulators (Netafim PRV-1, 100–300 kPa), and valves. Structural materials included galvanized steel pipes (Nigeria Steel Co.) and UV-treated polyethylene sheets (Agroplast, India). The tools used were a Dumpy level (Sokkia B40A, Japan), tripod, levelling staff, soil auger, core cutter, and measuring tape. Laboratory equipment included an oven (Memmert 100-800, Germany), an electronic weighing balance (Ohaus PA2102, USA), and a muffle furnace (Carbolite CWF 1200, UK). AutoCAD 2023 (Autodesk Inc., USA) was used for the irrigation system design, and IBM SPSS Statistics version 28.0 (IBM Corp., USA) was used for data analysis.

Levelling of Study Area

The study area was levelled using the reduced level (RL) approach to establish a uniform surface for irrigation design, following the procedure outlined by Punmia *et al*. (2018). The RL method involves setting a known datum point and measuring the elevation of other points using a Dumpy level. The differences in elevation were used to compute reduced levels, providing an accurate topographical profile of the greenhouse. This ensured even water distribution and prevented waterlogging during irrigation.

Soil Sampling and Characterization

Soil samples were collected using a soil auger at depths of 0–20 cm and preserved in airtight polyethylene bags for laboratory analysis. Tests were conducted according to BS 1377 (1990) standards. Bulk density was determined using the core cutter method, while porosity was calculated using bulk and particle densities. Permeability was assessed using the constant head test. Loss on ignition (LOI) was determined by heating oven-dried soil samples at 450°C for four hours in a muffle furnace, using Equation 1 and organic matter content was computed using the Van Bemmelen factor in Equation 2:

$$LOI(\%) = \frac{W^2 - W^3}{W^2 - W^1} \quad (1)$$

$$OMC = LOI(\%) \times 1.724 \quad (2)$$

Design and Construction of Drip Irrigation System

The drip irrigation system was designed to ensure high water-use efficiency and uniform distribution. The design capacity was 2.4 m³/day, sufficient to meet the peak evapotranspiration demand of the tomato crop. Hydraulic design was based on the Hazen-Williams equation for estimating head loss in Equation 3:

$$hf = \frac{10.67 . L . Q^{1.852}}{C^{1.852} . D^{4.87}} \quad (3)$$

Where; h_e is head loss (m), L is pipe length (m), Q is flow rate (m³/s), C is Hazen-Williams coefficient, and D is pipe diameter (m).

The total dynamic head (TDH) required for pump selection was calculated using Equation 4 as:

$$\text{TDH} = H_e + H_f + H_p \quad (4)$$

Where; He = elevation head, Hf = frictional losses, and Hp = required pressure at emitters. The pump was selected to deliver the required discharge and pressure efficiently.

Performance Evaluation

The irrigation depth and interval were determined based on soil properties and crop water requirements. Available Water Capacity (AWC) was computed using Equation 5:

$$\text{AWC} = (FC - WP) \times BD \times D \quad (5)$$

Where; FC = field capacity, WP = wilting point, BD = bulk density, and D = root zone depth. The irrigation interval was derived from Equation 6:

$$\text{Irrigation Interval (days)} = \frac{\text{MAD} \times \text{AWC}}{\text{ET}_\text{c}} \quad (6)$$

Where; MAD = Management Allowable Depletion and ETc = crop evapotranspiration.

Crop population was determined based on 40 cm × 40 cm spacing, resulting in 3750 stands per 600 m² greenhouse area.

Vegetable Growth Response

The vegetable growth response was assessed to determine the impact of different irrigation regimes on tomato (*Solanum lycopersicum L.*) performance under greenhouse conditions. A Randomized Complete Block Design (RCBD) with three irrigation treatments 100%, 80%, and 60% of crop evapotranspiration (ETc) and three replications was employed. Each 2 m × 2 m plot contained 25 plants spaced at 40 cm intervals, irrigated through a drip system regulated by a Rain Bird PRS-Dial pressure controller (USA) and monitored with a DAE AS200U-50 flow meter (China). Growth parameters including plant height, leaf count, stem diameter, and leaf area index (LAI) were measured weekly using standardized instruments, while fruit yield and water use efficiency (WUE = Y/I) were determined at maturity to evaluate irrigation effectiveness.

Results and Discussion

Soil Geotechnical Properties

The geotechnical characterization of the soil samples collected from the greenhouse site revealed important insights into their suitability for efficient crop production under a drip irrigation system. As shown in Table 1, the bulk density of the soil averaged 1.85 g/cm^3, which falls within the acceptable range of 1.3–1.9 g/cm^3 specified by BS 1377 (Part 2, 1990) and FAO (1990). This value indicates a moderately compacted soil that provides a balance between adequate aeration and water retention, thereby supporting root penetration and nutrient uptake. Similarly, this result agrees with the findings of Echebiri *et al*. (2025), who reported that bulk densities between 1.6 and 1.76 g/cm^3 promote optimal water infiltration and crop performance in greenhouse-based systems.

Furthermore, the soil's permeability coefficient, which averaged 1.15×10^{-4} cm/s, suggests a moderately permeable structure that ensures efficient drainage without excessive leaching. This value lies within the acceptable range of 10^{-3}–10^{-4} cm/s stipulated by BS 1377 (Part 5, 1990) and ASTM D2434. Consequently, the soil can facilitate steady water movement and oxygen exchange in the root zone, which are critical for plant physiological processes. This observation aligns with the results of Zapata-Sierra *et al*. (2021), who emphasized that soils with permeability within this range maintain suitable moisture balance for drip-irrigated vegetable crops. Hence, the permeability characteristics observed here are consistent with the hydraulic requirements of an efficient drip irrigation system.

In addition, the loss on ignition (LOI) recorded an average value of 2.45%, indicating a relatively low organic matter content within the soil matrix. Although this value is well below the 5% limit recommended by BS 1377 (Part 3, 1990) and USDA (2017), it still demonstrates the presence of moderate organic matter, which contributes to soil fertility and structural stability. Correspondingly, this result is comparable to the findings of Calderon and Dangi (2024), who noted that LOI values between 2% and 4% support favorable microbial activity and nutrient availability in greenhouse soils. Thus, the organic matter level in this site appears sufficient for sustaining plant growth while minimizing the risk of compaction or poor aeration.

Moreover, the natural moisture content of the soil averaged 8.8%, which is within the standard range of 5–15% established by BS 1377 (Part 2, 1990) and FAO (1990). This value reflects a moderately moist soil condition that supports both microbial activity and nutrient solubility, thereby enhancing crop development. It also indicates that the soil retains enough water to meet the initial crop water requirements before irrigation scheduling begins. In agreement, Alharbi *et al*. (2024) observed that soils with natural moisture content within this range provide a stable base for irrigation performance evaluation and water-use efficiency analysis. Therefore, the observed moisture level further supports the overall suitability of the greenhouse soil for tomato production.

Table 1: Geotechnical Properties of Soil Samples from the Greenhouse Site

Property	Sample 1	Sample 2	Average Value	Acceptable Standard Range
Bulk Density (g/cm³)	1.86	1.85	1.85	1.3–1.9 (BS 1377: Part 2, 1990; FAO, 1990)
Permeability (k) (cm/s)	2201×10^{-4}	857×10^{-4}	1.15×10^{-4}	10^{-3}–10^{-4} (BS 1377: Part 5, 1990; ASTM D2434)
Loss on Ignition (%)	2.68	2.22	2.45	≤5 (BS 1377: Part 3, 1990; USDA, 2017)
Natural Moisture Content (%)	7.64	9.93	8.8	5-15(BS 1377: Part 2, 1990; FAO, 1990)

Levelling and Spot Height

The levelling and spot height observation presented in Table 4.2 provides an essential topographical assessment of the greenhouse farm area, which measures 20 × 30 m. The survey was conducted using the reduced level (RL) approach with a dumpy level to establish height variations across the field. This process was vital in determining surface gradients and ensuring proper slope orientation for efficient water distribution under the drip irrigation system. As shown in the table, the benchmark (BM) was assigned an RL of 101.000 m, serving as the reference point for all subsequent readings within the greenhouse plot. The results reveal a gradual decrease in the reduced level values from the benchmark towards the far end of the site, indicating a gentle slope that can facilitate natural drainage. Specifically, from the benchmark (RL = 101.000 m) to Station 5 (RL = 100.719 m), the difference of 0.281 m suggests a uniform and consistent fall in elevation. Such a moderate slope is considered ideal for greenhouse layouts, as it supports adequate surface water movement without causing erosion or ponding. This observation aligns with the findings of Wang *et al*. (2025), who emphasized that mild slopes between 0.2 and 0.5 m per 20 m are optimal for drip irrigation installations due to their ability to maintain pressure uniformity and prevent emitter clogging.

Furthermore, the second setup of instrument height (H.I.) at 101.892 m reinforces the continuity of the levelling process across the second section of the field. The reduced levels in this section, ranging from 100.690 m at Station 6 to 100.434 m at change point 2 (CP2), reveal a cumulative fall of approximately 0.256 m. This consistent topographic gradient supports efficient lateral and longitudinal water flow, ensuring that water supplied from the drip emitters reaches all plant rows evenly. Correspondingly, this result corroborates the observation of Lakhiar *et al*. (2024), who reported that uniform elevation differentials within greenhouse environments enhance irrigation efficiency and promote balanced crop water uptake. In addition, the final segment of the levelling data, extending from Station 11 to the foresight (FS), maintained the same instrument height (H.I. = 101.550 m), with RL values decreasing gradually from 100.434 m to 100.165 m. This progressive reduction of 0.269 m suggests a stable and well-drained field surface, indicating that the area was properly graded. A well-levelled surface minimizes water stagnation, improves infiltration rates, and reduces the risk of uneven moisture distribution key factors in achieving high irrigation efficiency. This observation is in line with the study of Xing and Wang, (2024), who concluded that precise levelling enhances uniformity of soil moisture and fertilizer distribution in controlled irrigation systems.

Table 2: Levelling and Spot Height Observation for the Greenhouse Farm

Station	BS (m)	IS (m)	FS (m)	H.I. (m)	RL (m)
BM	1.215	—	—	102.215	101.000

1	—	1.324	—	102.215	100.891
2	—	1.356	—	102.215	100.859
3	—	1.402	—	102.215	100.813
4	—	1.447	—	102.215	100.768
5	—	1.496	—	102.215	100.719
CP1	—	—	1.525	102.215	100.690
6	1.202	—	—	101.892	100.690
7	—	1.268	—	101.892	100.624
8	—	1.312	—	101.892	100.580
9	—	1.359	—	101.892	100.533
10	—	1.426	—	101.892	100.466
CP2	—	—	1.458	101.892	100.434
11	1.116	—	—	101.550	100.434
12	—	1.242	—	101.550	100.308
13	—	1.286	—	101.550	100.264
14	—	1.314	—	101.550	100.236
15	—	1.359	—	101.550	100.191
FS	—	—	1.385	101.550	100.165

BM is Benchmark, BS is Backsight, IS is Intermediate Sight, FS is Foresight, H.I. is Height of Instrument and RL is Reduced Level.

Irrigation System Performance

The analysis provides a detailed evaluation of the system's operational characteristics and efficiency at varying discharge demands. The observed parameters, including total flow rate, pressure, head losses, and system efficiency, collectively determine the functional stability and energy requirements of the drip irrigation setup. Table 4.3 presents the hydraulic performance, head loss, and pump sizing of the greenhouse drip irrigation system under three irrigation regimes, 100%, 80%, and 60% of the crop evapotranspiration (ETc).

To begin with, the total flow rate decreased proportionally with a reduction in irrigation regime, dropping from 500 $L \cdot h^{-1}$ at 100% ETc to 305 $L \cdot h^{-1}$ at 60% ETc. This reduction indicates that lower irrigation scheduling directly minimizes water demand, which consequently influences pump selection and operational energy consumption. The average operating pressure, however, exhibited a slight fluctuation rising to 110 kPa at 80% ETc before reducing to 90 kPa at 60% ETc. This pressure variation may be attributed to slight differences in emitter backpressure caused by flow reduction and head distribution along the lateral lines. Similar findings were reported by Wang *et al*. (2024), who noted that pressure uniformity tends to vary slightly under partial flow conditions but remains within acceptable limits for efficient drip performance. In terms of emitter discharge, the average flow rates followed the expected downward trend, decreasing from 4.1 $L \cdot h^{-1}$ at 100% ETc to 2.47 $L \cdot h^{-1}$ at 60% ETc. This reduction is consistent with the lower water supply rates under deficit irrigation conditions. Furthermore, the head loss values (hf) also decreased with irrigation regime, from 2.6 m at full irrigation to 1.55 m at 60% ETc, reflecting reduced frictional losses due to smaller flow volumes. Minor losses, which account for local disturbances such as fittings and valves, ranged between 0.9 m and 1.2 m, indicating minimal system resistance. This observation corroborates the work of Ame *et al*. (2022), who emphasized that properly aligned lateral connections and uniform pressure compensation in emitters help reduce overall hydraulic losses in greenhouse drip networks.

Additionally, the total dynamic head (TDH) values are 24.8 m, 21.2 m, and 18 m for the respective irrigation regimes illustrate that lower water application levels significantly reduce the pumping head requirement. Consequently, the estimated pump power decreased from 0.047 kW at 100% ETc to 0.02 kW at 60% ETc, implying substantial energy savings under deficit irrigation. This inverse relationship between irrigation level and energy demand has also been observed by Ray and Majumder (2024), who reported that strategic irrigation scheduling in protected environments could reduce pumping costs by up to 40% without compromising water distribution uniformity. Regarding system uniformity and efficiency, the Christiansen Uniformity Coefficient (CU) and Emission Uniformity (EU) remained above 90% across all regimes, signifying excellent water distribution performance. Specifically, CU values ranged from 93.5% at full irrigation to 90.9% at 60% ETc, while EU values slightly declined from 90.2% to 86.6%. These small variations suggest that the drip system maintained high operational consistency even under reduced flow conditions. The overall system efficiency ranged from 91% to 88.6%, indicating that water losses were minimal throughout the operating range.

Table 3: Hydraulic performance, head loss and pump sizing under varying regimes

Irrigation Regime (% ETc)	**100% ETc**	**80% ETc**	**60% ETc**
Total Flow Q ($L \cdot h^{-1}$)	500	410	305
Avg. Operating Pressure (kPa)	101	110	90
Avg. Emitter Discharge ($L \cdot h^{-1}$)	4.1	3.28	2.47
Head Loss, h.f (m)	2.6	2.05	1.55
Minor Losses (m)	1.1	1.2	0.9
Total Dynamic Head, TDH (m)	24.8	21.2	18
Pump Power (kW)	0.047	0.032	0.02
CU (%)	93.5	92.7	90.9
EU (%)	90.2	89.4	86.6
System Efficiency (%)	91	90.1	88.6

Vegetable Growth Response

The results reveal a consistent pattern of growth across all treatments, with plants under full irrigation (100% ETc) exhibiting superior height performance throughout the study period. This indicates that water availability plays a significant role in determining the vegetative development of tomato crops under greenhouse conditions. Figure 1 presents the variation in tomato plant height under three irrigation regimes, 100%, 80%, and 60% of crop evapotranspiration (ETc) over a period of 63 days after sowing (DAS).

At the early growth stage (0–7 DAS), plant height ranged between 9.2 cm and 12.4 cm, reflecting the establishment phase of the seedlings when water requirements are relatively low. Although the differences among the treatments were modest, the 100% ETc treatment recorded the tallest seedlings (12.4 cm), followed by 80% ETc (11.0 cm) and 60% ETc (9.2 cm). As growth progressed to 14 DAS, the disparity widened, with plants under full irrigation is 30.6 cm significantly outperforming those under moderate is 27.8 cm and severe deficit irrigation is 23.5 cm. This trend indicates that adequate soil moisture availability enhances early root establishment and nutrient uptake. A similar observation was made by Abd El-Mageed *et al.* (2023), who reported that optimal irrigation at 100% ETc significantly promoted vegetative growth and stem elongation in tomato plants compared to deficit treatments.

As the plants entered the mid-growth stage (15–35 DAS), rapid height increments were observed across all regimes, although the magnitude of increase varied. At 21 DAS, tomatoes irrigated at 100% ETc reached an average height of 55.1 cm, compared to 48.9 cm and 39.6 cm under 80% and 60% ETc, respectively.

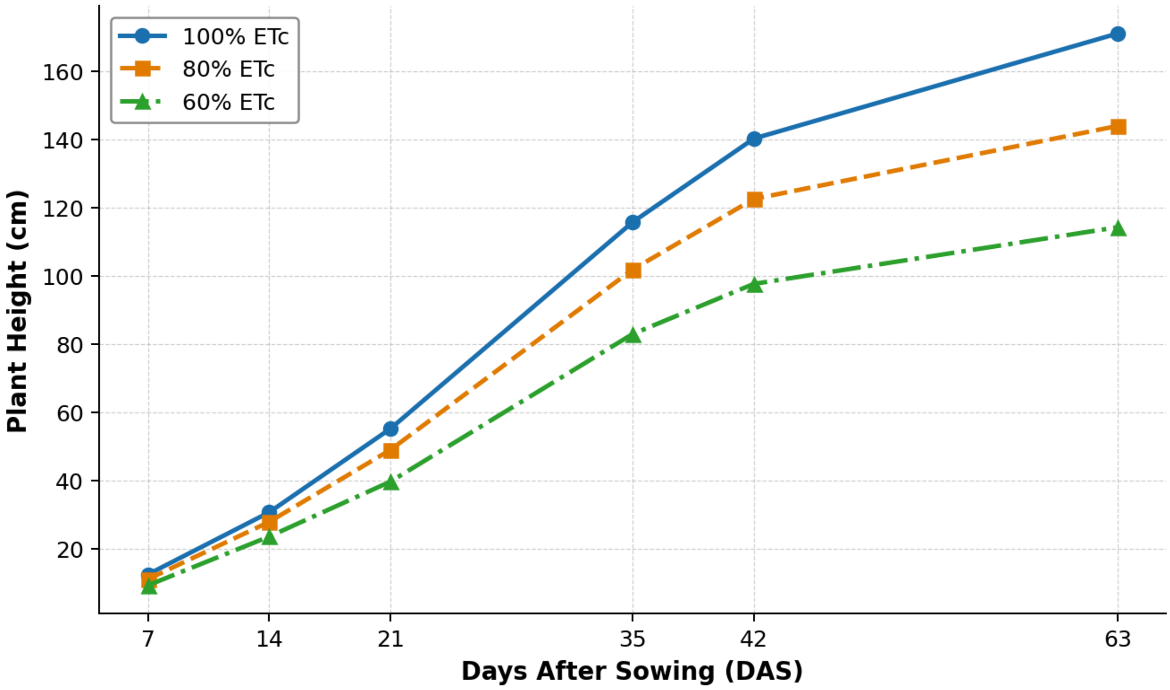

Figure 1: Plant Height (mm) Under Varying Irrigation Regimes

The continued increase in plant height corresponded with the period of vigorous vegetative expansion, which is highly sensitive to water availability. By 35 DAS, plants at full irrigation attained 115.7 cm, while those under 80% ETc and 60% ETc recorded 101.8 cm and 82.9 cm, respectively. These results align with the findings of Mukherjee *et al*. (2023), who noted that deficit irrigation reduces cell expansion and turgor pressure, leading to shorter plant stature in tomatoes.

Furthermore, during the later growth phase (36–63 DAS), the tomato plants maintained the same growth hierarchy, though the rate of height increment gradually stabilized. At 42 DAS, plants under 100% ETc reached 140.2 cm, while those under 80% ETc and 60% ETc achieved 122.5 cm and 97.6 cm, respectively. This pattern persisted until 63 DAS, when final mean heights were 171 cm, 143.9 cm, and 114.2 cm for 100%, 80%, and 60% ETc, respectively. The noticeable reduction in plant height under lower irrigation regimes demonstrates the adverse effect of moisture stress on vegetative growth. According to Chieb and Gachomo, (2023), water deficit reduces the rate of cell division and elongation, thereby limiting plant height and overall biomass accumulation. Moreover, the consistent superiority of the 100% ETc treatment throughout the experimental period suggests that full irrigation not only enhances vegetative vigor but also ensures a more uniform canopy structure, which is essential for optimal photosynthetic efficiency and fruiting potential. In contrast, the reduced heights observed under 80% and 60% ETc highlight the physiological adaptation of tomato plants to water stress, possibly through stomatal regulation and reduced transpiration rates. This finding agrees with the study by El–Metwally *et al*. (2022), who observed that tomato plants subjected to water stress exhibit slower vertical growth but may compensate with improved water use efficiency under controlled deficit irrigation conditions.

Figure 2 illustrates the variation in the number of leaves of tomato plants grown under three irrigation regimes, 100%, 80%, and 60% of the crop evapotranspiration (ETc) over a 63-day growth period. The pattern of leaf development demonstrates a clear dependence on the level of water availability, with plants under full irrigation consistently producing more leaves than those subjected to water deficit conditions. This observation indicates that adequate soil moisture promotes optimal vegetative growth, enhancing the formation of photosynthetic structures necessary for efficient biomass accumulation and yield potential.

At the early stage of growth (0–7 DAS), the tomato plants exhibited minimal variation in leaf number across treatments, reflecting their initial adaptation phase following transplanting. The plants under 100% ETc recorded an average of four leaves, slightly higher than those under 80% ETc and 60% ETc, both with three leaves. As growth progressed to 14 DAS, differences among the treatments became more distinct, with plants under 100% ETc developing nine leaves compared to eight and six leaves under 80% and 60% ETc, respectively. This suggests that even at the early vegetative phase, water stress begins to influence leaf initiation and expansion. Similar findings were reported by Abdulridha *et al*. (2020), who observed that limited irrigation during the early growth stages of tomatoes led to delayed leaf emergence and smaller canopy formation. As the plants advanced to the mid-growth period (15–35 DAS), a steady increase in leaf production was observed under all regimes, though the magnitude of increase remained highest under full irrigation. At 21 DAS, tomato plants irrigated at 100% ETc produced 16 leaves on average, followed by 14 and 11 leaves under 80% and 60% ETc, respectively. This difference widened further by 35 DAS, when plants under 100% ETc reached 32 leaves, while those under 80% and 60% ETc recorded 27 and 19 leaves. These results clearly demonstrate that moisture deficiency limits leaf proliferation, likely due to reduced turgor pressure and inhibited cell expansion. This observation is consistent with the study of Alshami *et al*. (2023), who found that deficit irrigation significantly reduced leaf count and canopy coverage in tomato crops, leading to lower photosynthetic activity and slower vegetative development.

During the later growth stages (36–63 DAS), the pattern of leaf production continued with marked differences among the treatments. At 42 DAS, plants under 100% ETc had an average of 38 leaves compared to 33 and 24 leaves under 80% and 60% ETc, respectively. Similarly, by 63 DAS, the fully irrigated plants attained 46 leaves, while those under moderate and severe water deficits recorded 39 and 28 leaves, respectively. These differences signify the cumulative effect of water availability on leaf expansion rate and longevity. According to Xu *et al*. (2022), adequate irrigation maintains leaf turgidity and enhances chlorophyll synthesis, whereas moisture deficit accelerates leaf senescence and reduces leaf area index in tomato plants. The consistent superiority of the 100% ETc treatment indicates that sufficient irrigation not only enhances leaf count but also supports broader canopy development, which improves light interception and photosynthetic efficiency. On the other hand, the reduced leaf production observed under 80% and 60% ETc may be attributed to physiological adjustments that prioritize water conservation over vegetative growth, a typical adaptive response to drought stress.

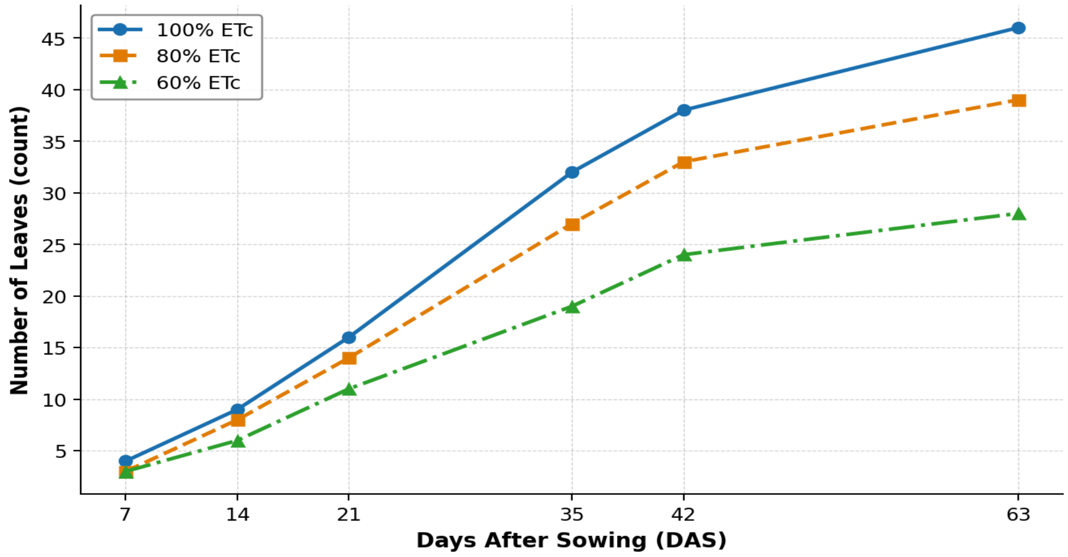

Figure 2: Number of Leaves (count) Under Varying Irrigation Regimes

Figure 3 illustrates the tomato yield in grams per plant obtained under three irrigation regimes, 100%, 80%, and 60% of the crop evapotranspiration (ETc) throughout the 63-day growing period. The results clearly show that fruit yield increased progressively with plant maturity, and significant differences were observed among the irrigation levels. Notably, the highest yield occurred under the 80% ETc regime, followed by the 100% ETc and 60% ETc treatments. This pattern indicates that moderate water deficit enhanced yield efficiency compared to full irrigation, highlighting the advantage of controlled deficit irrigation in improving both water use and crop productivity in greenhouse tomato cultivation.

At the early growth stage spanning from 0 to 21 days after sowing, no yield was recorded under any of the irrigation regimes because the plants were still in their vegetative phase, during which fruiting had not yet commenced. Yield formation began at 28 days after sowing when tomatoes irrigated at 80% ETc recorded a yield of 12.4 g/plant, slightly exceeding those at 100% ETc, which had 10.1 g/plant, and those at 60% ETc, which produced 8.3 g/plant. This early variation suggests that mild water stress might have stimulated early flowering and fruit initiation, possibly due to hormonal adjustments such as elevated abscisic acid activity that promotes reproductive development. A comparable finding was reported by Ebstu and Muluneh, (2025), who observed that moderate deficit irrigation encouraged early flowering and fruiting in tomatoes without compromising overall yield quality. As the plants transitioned into their active fruiting phase between 29 and 42 days after sowing, yield differences among the treatments became more pronounced. At 35 days, the 80% ETc treatment produced 46.7 g/plant, outperforming the 100% ETc regime with 39.4 g/plant and the 60% ETc regime with 28.9 g/plant. This trend continued until 42 days after sowing when tomatoes under 80% ETc recorded 112.8 g/plant, compared with 96.5 g/plant for 100% ETc and 68.2 g/plant for 60% ETc. The consistent superiority of the 80% ETc treatment suggests that moderate water deficit enhanced yield efficiency, possibly through improved assimilate allocation and greater fruit concentration. He *et al*. (2024) similarly reported that tomatoes exposed to mild water stress produced higher fruit dry matter and total soluble solids, demonstrating improved water use efficiency and better fruit quality compared to fully irrigated plants.

During the later stage of development, from 43 to 63 days after sowing, fruit yield continued to rise across all treatments; however, the 80% ETc regime maintained a clear advantage. At

49 days after sowing, tomatoes under 80% ETc produced 185.6 g/plant, followed by 158.9 g/plant under full irrigation and 115.4 g/plant under severe deficit. By the end of the growth cycle at 63 days, the final yield reached 310.4 g/plant for 80% ETc, 262.8 g/plant for 100% ETc, and 186.1 g/ plant for 60% ETc. The substantial yield gap between 80% and 60% ETc indicates that while moderate water deficit can enhance productivity, excessive reduction in water supply leads to physiological stress that restricts fruit development and size. This observation agrees with the findings of Dietz *et al*. (2021), who noted that severe water deficit reduces photosynthetic capacity and limits carbohydrate translocation to fruits, thereby diminishing yield potential.

Furthermore, the superior yield performance under the 80% ETc regime suggests that mild water stress may have optimized physiological responses by maintaining a balanced relationship between vegetative growth and fruit production. In contrast, excess water under full irrigation likely promoted vigorous vegetative expansion at the expense of reproductive output, leading to reduced fruit yield efficiency. This explanation aligns with the report by Alghamdi *et al*. (2024), who found that slight water deficit improved tomato yield by enhancing fruit set and minimizing flower drop. Thus, while full irrigation supports luxuriant growth, controlled water limitation appears more beneficial in achieving higher fruit yield and improved water use efficiency.

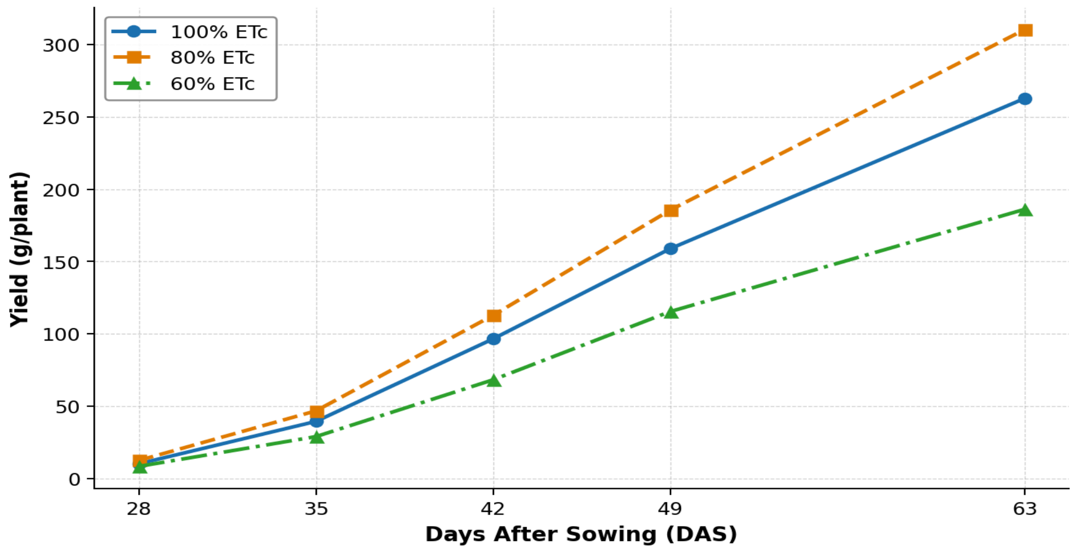

Figure 3: Tomato Yield (g/plant) Under Varying Irrigation Regimes

Conclusion

The study concluded that the soil at the greenhouse site possessed adequate geotechnical characteristics for sustainable irrigation performance, while the uniform slope of 101.000–100.165 m ensured stable water flow and efficient system layout. Hydraulic evaluation confirmed high operational efficiency and energy conservation across regimes, with 80% ETc providing the optimal balance between yield and water use. It is therefore recommended that periodic soil testing, system maintenance, and re-levelling be conducted, while future installations should maintain gentle slopes and use energy-efficient pumps. Farmers are further encouraged to adopt 80% ETc irrigation with automated control systems to optimize greenhouse tomato production sustainably.

Acknowledgement
We express our profound gratitude to Almighty God for His steadfast support and divine guidance throughout the course of this research. His grace enabled us to navigate every challenge successfully, and for that, we are truly thankful. We sincerely acknowledge the invaluable support, knowledge, and encouragement provided by our lecturers, whose contributions greatly enriched this work.

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