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Enhancing Water Security Through Automated Drip Irrigation: Impacts on Soil Moisture Dynamics and Brinjal Yield in Semi-arid Systems

Maduwantha N. Herath[1], Mayuresh Niranjan[1], Kandiah Pakeerathan[2], Jameson Arasakesary Sinnathurai[2], and Kannan Nadarajah[1]

Abstract

Improving irrigation efficiency is essential for sustaining vegetable production in water-limited environments, yet field-scale evaluations of practical time-based automated drip irrigation systems remain limited. This study compared an Automated Drip Irrigation Treatment (ADIT) employing scheduled time-based irrigation with a Manually Operated Drip Irrigation Treatment (MDIT) under polythene mulch for brinjal (*Solanum melongena L.*) cultivation in sandy loam soil during the 2025 *Yala* season in Sri Lanka. Soil moisture dynamics, irrigation uniformity, root distribution, wetting patterns, crop water requirement, yield, and irrigation water-use efficiency (IWUE) were evaluated using field measurements together with CropWat and HYDRUS-1D simulations. ADIT achieved consistently higher irrigation performance, with Christiansen's coefficient of uniformity (CU) of 91–93%, emission uniformity (EU) of 90–92%, and distribution uniformity (DU) of 88%, compared with 75–80%, 78–82%, and 72%, respectively, under MDIT. Improved water distribution resulted in more stable root-zone soil moisture conditions, while HYDRUS-1D simulations predicted substantially lower deep percolation losses under ADIT than MDIT during crop development. Field observations also showed greater lateral root spread (40.7 cm vs 33.0 cm), higher irrigation water-use efficiency (4.91 vs 3.37 kg m^{-3}), and greater marketable yield (22.3 vs 16.7 t ha^{-1}; 2.35 vs 1.62 kg $plant^{-1}$) under ADIT. Because the evaluated irrigation configurations differed in hydraulic characteristics as well as irrigation control strategy, and the study was conducted as a single-season field-scale pilot without replicated treatment plots, the findings should be interpreted as comparative evidence of system-level performance rather than effects attributable solely to automation. Nevertheless, the evaluated ADIT configuration demonstrated considerable potential for improving irrigation performance and water productivity under sandy loam, semi-arid conditions, warranting validation through replicated experiments using hydraulically identical irrigation systems.

Keywords

automated irrigation, brinjal, drip irrigation, hardpan, manual irrigation, polythene mulching, time-based, wetting front

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[1]Department of Agricultural Engineering, Faculty of Agriculture, University of Jaffna, Kilinochchi, Sri Lanka
[2]Department of Agricultural Biology, Faculty of Agriculture, University of Jaffna, Kilinochchi, Sri Lanka

Corresponding author:
Kannan Nadarajah, Department of Agricultural Engineering, Faculty of Agriculture, University of Jaffna, Kilinochchi, Sri Lanka.
Email: nkannan@univ.jfn.ac.lk

Highlights

Time-based automated drip irrigation tested for brinjal crops.
Automation improved water distribution and soil moisture stability.
Yield increased 33.5% vs manual irrigation at the same water input.
Water-use efficiency improved by 46% with automated scheduling.
Time-based control alone improved agro-hydrological performance.

1. Introduction

Continued global population growth is increasing pressure on agricultural production systems and limited freshwater resources (Falkenmark & Rockström, n.d; Murray et al., 2018). Agriculture accounts for approximately 70% of global freshwater withdrawals, yet only a small fraction of Earth's water is accessible for human use (Alexandratos, 2012; Yang et al., 2023a, 2023b). Under increasing climate variability and water scarcity, improving irrigation efficiency is central to climate change adaptation and water security (Falkenmark & Rockström, 2006; Van Bavel, 2013). In this context, innovative irrigation technologies are essential for sustaining crop productivity while reducing water demand.

Drip irrigation is widely recognized for its ability to reduce water use by 20–40% compared to conventional systems by minimizing evaporation and runoff losses (Guo & Li, 2024; Yang et al., 2023b). Its performance can be further enhanced through advanced monitoring approaches, including remote sensing and machine learning, which improve irrigation uniformity and system management (Boninsenha et al., 2025). The use of polythene mulch complements drip systems by conserving soil moisture, increasing topsoil water content by 9–13%, and reducing evapotranspiration losses by up to 45% (Song et al., 2024). Together, these approaches support improved water-use efficiency and more stable root-zone moisture conditions, which are critical under semi-arid climates (Li et al., 2020).

Recent developments in irrigation automation, including time-based and sensor-based systems, enable precise water application aligned with crop growth stages and environmental conditions. These systems can enhance adaptability to climate variability, reduce labor constraints resource-use efficiency, including fertilizer savings of 20–30% when combined with optimized fertigation strategies (AL-agele et al., 2021; Dong et al., 2023). Despite these advances, there remains limited field-based understanding of how automated irrigation combined with mulching influences soil water dynamics, irrigation uniformity, and crop response under semi-arid conditions.

Brinjal (*Solanum melongena* L.) is a widely cultivated vegetable with high economic value and adaptability to semi-arid environments (Chinthagunti et al., 2018). While previous studies have demonstrated the benefits of drip irrigation for improving yield and water-use efficiency (Aujla et al., 2007; Manikandan & Ravikumar, 2020), less attention has been given to the underlying soil-water processes that govern crop performance. In particular, the combined effects of irrigation automation and mulch-mediated moisture conservation on soil moisture distribution, root development, and irrigation uniformity remain insufficiently quantified.

Recent advances in irrigation automation have increasingly focused on sensor-based, Internet of Things (IoT), and data-driven control systems that use real-time soil or environmental information to regulate irrigation (Anoop & Bala, 2024; Vallejo-Gómez et al., 2023). Sensor-based approaches can provide responsive irrigation management by adjusting water application according to measured soil-water conditions, whereas conventional timer-based systems operate according to predefined irrigation intervals and durations (Kaptein et al., 2019). However, the technical architecture and monitoring requirements associated with advanced smart irrigation systems may constrain their practical deployment in resource-limited agricultural settings. Consequently, simpler time-based automation remains relevant where the primary management objective is to standardize irrigation timing and duration while reducing dependence on manual operation. Recent evidence from smallholder-oriented irrigation development has similarly highlighted the potential of low-cost timer-based drip systems as practical alternatives in resource-constrained farming environments (Hasbi et al., 2026).

This study evaluates a time-based automated drip irrigation system under polythene mulch compared to a manually operated system for brinjal cultivation in semi-arid conditions. It focuses on soil moisture dynamics, irrigation uniformity (CU, EU, DU), root distribution, and water-use efficiency. H1: The integrated automated drip irrigation configuration (ADIT) will exhibit higher irrigation uniformity and more stable soil moisture dynamics than the manually operated drip irrigation configuration (MDIT) under field conditions. H2: The integrated ADIT configuration will be associated with greater lateral root development, higher irrigation water-use efficiency, and improved crop productivity than the manually operated configuration under the conditions evaluated. The specific objectives were to: (i) compare soil moisture dynamics under the two irrigation configurations; (ii) evaluate irrigation application uniformity; (iii) assess wetting-front development and root distribution characteristics; and (iv) examine irrigation water productivity and crop yield responses under field conditions. By integrating these factors, the study provides insight into irrigation strategies that enhance water productivity and support climate-resilient vegetable production in water-limited agroecosystems.

2. Materials and Methods

2.1. General Research Background

This study was conducted as a field-scale comparative pilot evaluation of two drip irrigation configurations under operational farming conditions. A schematic summary of the overall study workflow is provided in the Supplemental Material (Figure S1).

2.2. Materials

The planting material used in this study was Indian F1 hybrid brinjal variety 704 (*Solanum melongena* L. cv. Sungro No. 704), obtained from a government seed production farm in Paranthan, Kilinochchi, Sri Lanka. Healthy and uniform seedlings were selected for transplantation to ensure consistency in plant growth.

Field equipment and laboratory facilities were provided by the Environmental and Hydro-Research Laboratory, Department of Agricultural Engineering, Faculty of Agriculture, University of Jaffna, Kilinochchi, Sri Lanka. Soil samples collected from the experimental field were analyzed using standard laboratory procedures to determine their physical and chemical properties.

The experiment was conducted using both automated and manual drip irrigation systems, installed by Northern Micro Irrigation Pvt. Ltd. The automated system was equipped with a 1.5 hp submersible pump (FLINT-WQD6-18-1.1G, 2″, 60 ft), while the manual system used a 1 hp submersible pump (DEEPSTEEL-QDX1.5-32-0.75F, 1″). Both systems consisted of HDPE mainlines (60 mm) and LDPE lateral lines (16 mm), fitted with 4 L h^{-1} online drippers connected via 40 cm microtubes (3 mm) and appropriate connectors. A 120-mesh, 2-inch filter (approximately 125 μm aperture) and a 130 cm venturi system were incorporated into both setups to facilitate fertigation and prevent clogging.

The automated system was controlled using a microcontroller panel (X-Core series, Hunter Industries) integrated with a soil moisture sensor (Soil-Clik), connected via 18 AWG (1 mm) direct-burial wires. Meteorological data used for irrigation scheduling and soil moisture assessment were obtained from the Regional Agricultural Research and Development Center (RARDC), Iranaimadu, Sri Lanka. The automated drip irrigation system was operated using a predefined irrigation schedule designed to apply the same irrigation volume throughout the growing season. A Soil-Clik soil moisture sensor (Hunter Industries, USA) was integrated with the controller to monitor field moisture conditions and to suspend irrigation under excessively wet soil conditions when necessary. The sensor was not used to determine irrigation scheduling decisions, which remained time-based throughout the study.

Biofertilizers (*Bacillus subtilis*, *Trichoderma*, and *Pseudomonas*) marketed as Great Harvest Bio Fertilizer, along with a liquid foliar fertilizer (AGLUKON Biofol 11-8-6). Biofertilizer applications were conducted uniformly across both irrigation treatments as part of the routine crop management practices at the study site, sourced from a local agrochemical supplier in Kilinochchi and applied for fertigation and basal treatments.

2.3. Field Preparation

The experiment was conducted at a community research plot for smart agriculture in the dry zone of Thiruvaiaru, Kilinochchi, Sri Lanka. The site is located at 9°20′59.2″ N latitude and 80°25′47.9″ E longitude. The study commenced on 16 June 2025 to 28 September 2025 during the *Yala* season (April – September). This region falls within Sri Lanka's dry zone, characterized by an average annual rainfall of approximately 1325 mm, about 75% of which occurs between September and December during the North-East monsoon. The terrain is predominantly flat, with soils classified as Red Yellow Latosols, Solodized Solonetz, Solonchaks, and Alluvial soils (Dharmasena, 2011).

The land was prepared using a primary tillage implement mounted on a four-wheel tractor (Standard-350di) to a depth of 20 cm, achieving a fine tilth. Separate plots were established for automated and manual drip irrigation treatments. Planting beds were constructed with a width of 80 cm and a spacing of 30 cm between beds. Each bed was covered with 25 μm black polythene mulch, with 10 cm diameter holes for transplanting.

The automated drip irrigation treatment (ADIT) plot consisted of 60 planting beds with 20 plants per bed, covering an area of 1269.5 m^2. The manual drip irrigation treatment (MDIT) plot comprised 42 planting beds with 25 plants per bed, covering

1018.5 m^2, as shown in Figure 1. All agronomic practices during land preparation followed the recommendations of the Department of Agriculture (DOA) of Sri Lanka. Although the treatment plots differed in total area and plant population, a standardized sampling protocol was adopted for both treatments. Each plot was subdivided into predefined sampling zones to improve spatial representation, and observations were collected from an equal number of randomly selected plants within these zones at each measurement interval. Crop yield was subsequently normalized and reported on an area basis (t ha^{-1}) to facilitate comparison between treatments.

Basal fertilization was carried out uniformly in both irrigation configurations following the fertilizer recommendations of the Sri Lankan Department of Agriculture for brinjal production. Chemical fertilizers consisted of urea ($CO(NH_2)_2$), diammonium phosphate ($(NH_4)_2HPO_4$), and sulphate of potash (K_2SO_4). In addition, a commercial biofertilizer containing *Bacillus subtilis*, *Trichoderma*, and *Pseudomonas* (Great Harvest Bio Fertilizer) together with a liquid foliar fertilizer (AGLUKON Biofol 11-8-6) was applied through the drip irrigation system as part of the routine fertigation programme. Fertilizer application schedules and general crop management practices, including pest and disease management, were maintained uniformly across both irrigation configurations throughout the experimental period to minimize non-irrigation sources of variation.

2.4. Drip Systems Installation

For both the Automated Drip Irrigation Treatment (ADIT) and the Manual Drip Irrigation Treatment (MDIT), two emitters were installed per planting hole. Emitters were positioned approximately 10 cm apart and located about 40 cm from the lateral line, ensuring effective wetting of the root zone while minimizing deep percolation losses.

The layout was designed to achieve uniform water distribution around each plant. Irrigation events in the ADIT system were initiated according to the predefined schedules shown in Table 1. The Soil-Clik sensor was used to monitor field moisture conditions and provide a supplementary safeguard against irrigation under excessively wet conditions. Detailed specifications of both irrigation systems are provided in Table 1, and the experimental layout is illustrated in Figure 1.

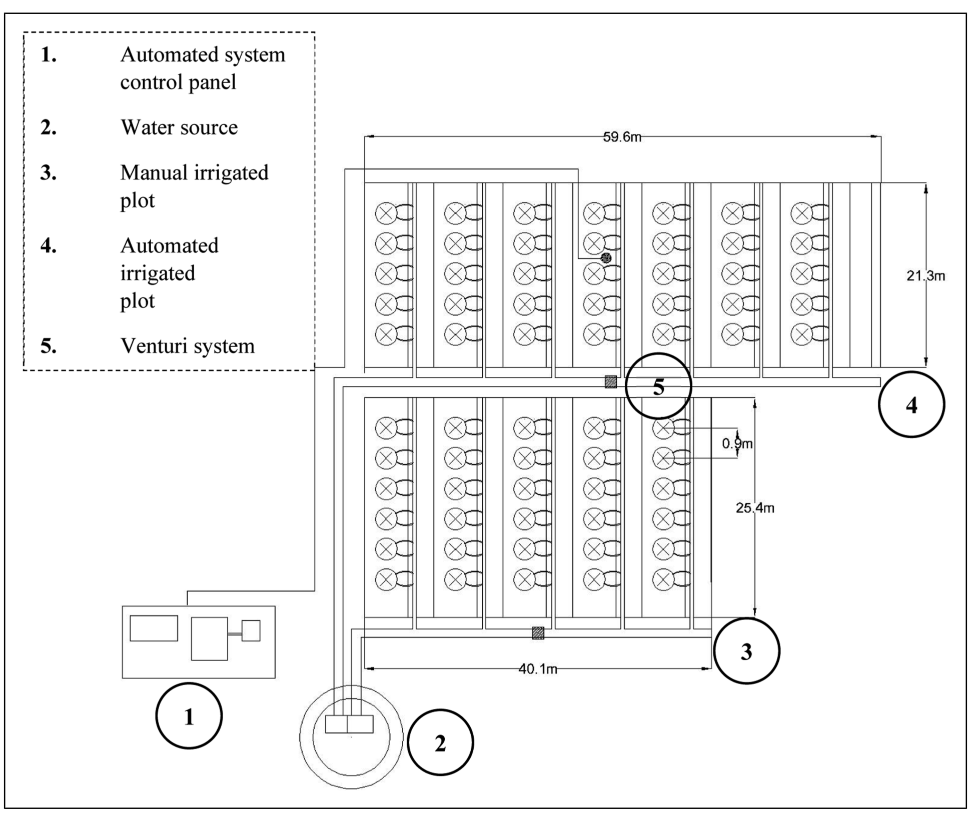

Figure 1. Experimental plot design and drip system layout of ADIT and MDIT

Table 1. Comparison of System Specification Between Automated and Non-automated Drip Irrigation Systems

Parameter	Automated drip irrigation treatment (ADIT)	Manual drip irrigation treatment (MDIT)
Irrigation scheduling	6.00 a.m. - 6.30 a.m. 6.00 p.m. - 6.30 p.m.	8.00 a.m. - 9.00 a.m. 6.00 p.m. - 7.00 p.m.
Emitter flow rate (standard drippers)	8 Lh^{-1}	4 Lh^{-1}
Emitter lateral spacing	90 cm x 90 cm	90 cm x 90 cm
Volume per irrigation	4 L per plant (based on scheduling)	4 L per plant (manual timing)
Operating/working pressure	14 - 17 PSI (regulated)	14 - 17 PSI (manual valve control)
Pump specification	1.5 HP, submersible pump, head 50 m	1 HP, submersible pump, head 50 m
Filter system	Mesh filter at main line and venturi	Mesh filter at main line and venturi
Operating modes	Time based + soil moisture sensor input automated, semi-automated, and manual	Manual operation
Backup operation	3 V (CR2032) battery (retains date and time) for microcontroller unit	None
Soil moisture monitoring	Capacitive moisture sensor (Soil-Clik), SC-Probe at 15 cm depth	None
Control unit	Microcontroller (Arduino ARD-A000053) with LCD interface	Not applicable
Energy requirement	1.0 kWh per irrigation event (pump + controller)	0.75 - 1.0 kWh per irrigation event (pump only)

2.5. Seedling Transplantation

Brinjal (*Solanum melongena* L., Indian F1 hybrid 704) seedlings were transplanted on 20 June 2025 after 15 days of nursery growth in polybags. Basal fertilizer was applied at recommended rates using urea ($CO(NH_2)_2$), sulphate of potash (K_2SO_4), and diammonium phosphate ($(NH_4)_2HPO_4$).

Manual hand weeding was carried out one week after transplanting. Irrigation was applied according to the respective treatment schedules described in Table 1.

2.6. Irrigation Management and Experimental Design

Both ADIT and MDIT treatments received a daily irrigation volume of 8 L per plant across all growth stages. Application rates were 8 L h^{-1} for ADIT and 4 L h^{-1} for MDIT (Table 1). Although the ADIT and MDIT systems differed in pump capacity and emitter discharge characteristics, both systems were operated to satisfy the irrigation requirements of the crop according to their respective schedules. Consequently, treatment comparisons were based on the performance of the overall irrigation configurations rather than differences in total irrigation water supplied. It should be noted that variations in application rate and irrigation duration between systems may have influenced soil water dynamics and crop response.

Soil moisture dynamics were analyzed using HYDRUS-1D (version 4.03), which simulated vertical water movement in the root zone throughout the crop cycle. Field measurements of soil moisture were obtained using digital tensiometers (UZI-SMT50-LR) connected to a voltage data logger (HIOKI-LR5043) and data collector (HIOKI-LR5092-20). Tensiometers were installed 10 cm from the plant stem, and readings were recorded during the vegetative, flowering, and fruiting stages (C. C. et al., 1998). Plant growth parameters, including canopy height, canopy spread, and root distribution (horizontal and vertical), were measured at 4-day intervals using a measuring tape to assess crop response under each irrigation treatment.

The study was conducted as a field-scale pilot evaluation comprising one plot per irrigation treatment. Although independent treatment replication was not implemented, each treatment plot was divided into predefined sampling zones to account for within-plot spatial variability. At each observation date, measurements were collected from randomly selected plants within these zones using an identical sampling protocol for both treatments. Repeated observations collected throughout the growing season were used to characterize treatment performance; however, the absence of independent treatment replication should be considered when interpreting the findings. Consequently, comparisons between irrigation configurations are presented descriptively, and inferential statistical analyses between treatments were not performed. The reported observations should therefore be interpreted as configuration-level responses under the conditions evaluated rather than statistically validated treatment effects.

2.7. Measured Parameters

2.7.1. Soil Analysis

The performance of the irrigation systems and their effects on soil-water dynamics were evaluated using key parameters, including irrigation uniformity, soil moisture status, wetting pattern characteristics, root distribution, and water-use efficiency.

Prior to transplantation, soil samples from the experimental field were analyzed using standard procedures to determine their physical and chemical properties (Table 2). Soil texture was determined using the pipette method based on sedimentation principles derived from Stokes' law (Weil & Brady, 2017). Organic matter content was measured using the Walkley–Black method, and hydraulic conductivity (Ks) was determined using the auger hole method. Field capacity (FC) was measured gravimetrically after saturation and drainage (Hillel, 2004), while permanent wilting point (PWP) was estimated using plant-based or pressure plate methods (Bethune et al., 2008).

Particle size distribution was further verified using dry sieve analysis (Robertson et al., 1984). Particle density (ρp) and bulk density (ρb) were determined using pycnometer and core sampler methods, respectively (Brogowski et al., 2015). Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil-water extract using standard meters. Soil porosity (θ) and water-holding capacity (WHC) were calculated from density and moisture parameters (Hillel, 2004; Weil & Brady, 2017;).

Residual (θ_r) and saturated (θ_s) water contents were estimated using pedotransfer functions (Rosetta model), based on soil texture and bulk density (Schaap et al., 2001). Soil water retention characteristics were described using the van Genuchten model.

Irrigation uniformity was evaluated using Christiansen's Uniformity Coefficient (CU), Emission Uniformity (EU), and Distribution Uniformity (DU), calculated following standard procedures (Keller & Bliesner, 1990).

2.7.2. Crop Growth and Moisture Dynamics

Measurements were collected from randomly selected plants located within predetermined rows of each treatment plot. Approximately ten plants per observation event were evaluated at four-day intervals throughout the growing season. Soil moisture conditions were monitored using a TRI-SMT50-LR digital tensiometer. Soil water tension readings were converted to volumetric soil moisture content (%) using the manufacturer-provided conversion relationship supplied for the instrument. No site-specific calibration was performed, and the converted moisture values were used to characterize temporal soil moisture dynamics. Root distribution measurements were performed by carefully excavating the entire root system of two randomly selected plants from each predetermined sampling subplot up to 15 sampled plants per treatment to minimize root damage. The surrounding soil was gently removed manually, and adhering soil particles were washed away using clean water to expose the complete root system. Vertical root spread was determined by measuring the maximum taproot length from the stem base to the root tip using a measuring tape. Horizontal root spread was determined by measuring the maximum lateral root extension from the stem base to the outermost visible lateral roots in opposing directions. Measurements were recorded for randomly selected plants at four-day intervals throughout the observation period to characterize changes in root development under each irrigation configuration.

Net water requirement (NWR) and crop water requirement (CWR) were estimated based on soil moisture conditions, effective root zone depth, and evapotranspiration. Reference evapotranspiration (ETo) and crop evapotranspiration (ETc) were computed using the CROPWAT (version 8.0) model with meteorological data obtained from the Regional Agricultural Research and Development Center (RARDC).

Soil moisture dynamics, including depletion and wetting patterns, were analyzed using both field measurements and HYDRUS-1D simulations. Crop water requirements were estimated using CROPWAT based on stage-specific crop coefficient (Kc) values of 0.60, 1.05, 1.05, and 0.80 for the initial, development, mid-season, and late-season growth stages, respectively. Plant growth parameters, including canopy height, canopy spread, and root distribution, were measured at regular intervals using standard field methods. Canopy area was estimated using the Ramanujan approximation for elliptical geometry. The soil water retention characteristics used in the HYDRUS-1D simulations were described using the van Genuchten parameters presented in Table 2, which were subsequently incorporated into the MATLAB-based wetting pattern simulations. The soil hydraulic parameters required by the van Genuchten–Mualem model, including residual water content (θr), saturated water content (θs), inverse air-entry parameter (α), pore-size distribution parameter (n), and saturated hydraulic conductivity (Ks), were estimated using the Rosetta Lite hierarchical pedotransfer model (Schaap et al., 2001). Soil texture (sand, silt, and clay fractions) and measured bulk density of the experimental soil were used as input variables for the parameter estimation. The Rosetta Lite implementation was accessed through the USDA Salinity Laboratory online interface, and the estimated hydraulic parameters were subsequently used for HYDRUS-1D simulation of soil water movement.

2.8. Data Analysis and Interpretation

Experimental data were analyzed primarily using descriptive statistical methods to summarize treatment responses. Descriptive statistical analyses were performed to summarize irrigation performance, soil moisture dynamics, root distribution characteristics, and crop productivity under the two irrigation configurations. Means and variability measures were calculated where repeated observations were available. Due to the field-scale pilot nature of the study, consisting of a single treatment plot for each irrigation system, treatment comparisons were interpreted as observed differences between irrigation configurations rather than as formal replicated treatment tests. Microsoft Excel (version 2108) was used for data organization and preliminary analysis. MATLAB (version R2025b) was used for numerical modeling, including soil moisture dynamics, wetting front simulation, and irrigation performance analysis (Phogat et al., 2013). HYDRUS-1D simulations were used to estimate vertical soil-water movement and wetting-front depth. These outputs were subsequently imported into MATLAB to construct contour-based visualizations of wetting-front distribution.

The irrigation treatments were established in adjacent plots within the same field environment to reduce variation arising from soil and climatic factors. Although formal randomization of treatment assignment was not implemented, identical agronomic management practices and sampling procedures were applied across treatments. Consequently, the findings should be interpreted within the context of a field-scale pilot evaluation.

3. Results and Discussion

3.1. Physiochemical Properties of Soil

The baseline physicochemical properties of the experimental soil are presented in Table 2. The soil was classified as sandy loam based on pipette analysis (Weil & Brady, 2017), which is typically associated with moderate water-holding capacity and relatively high infiltration rates.

The saturated hydraulic conductivity (Ks) was 198.7 mm day^{-1}, indicating high permeability consistent with coarse-textured soils. This characteristic supports rapid infiltration and redistribution of water within the soil profile, which is advantageous for drip irrigation systems in promoting effective wetting patterns (Zhang et al., 2015). However, high permeability may also increase the risk of deep percolation losses, particularly under fixed, time-based irrigation schedules.

Soil organic matter content was low (1.21 ±0.05%), which is typical of arid and semi-arid regions where high temperatures accelerate organic matter decomposition (Saxton & Rawls, 2006). Low organic matter can limit soil aggregation and water retention capacity, potentially reducing the efficiency of drip irrigation systems (Weil & Brady, 2017).

The soil pH was neutral (7.10 ±0.01), which is suitable for brinjal cultivation (Raja et al., 2019). Electrical conductivity (0.43 dS m^{-1}) indicated non-saline conditions, suggesting no salinity-related constraints to crop growth (Ayers & Westcot, 2024). Overall, the combination of high permeability and low organic matter highlights the importance of precise irrigation

Table 2. Selected Soil Physio-Chemical Properties at the Experimental Site

Parameter	Unit	Value/Range
Soil texture	a.u.	Sandy loam
Organic matter content	% (w/w)	1.21 ±0.05
Hydraulic conductivity (Ks)	mmday^{-1}	198.7 ±0.3
Field Capacity (FC)	mmm^{-1}	124 ±2 (12.4% v/v)
Permanent Wilting Point (PWP)	mmm^{-1}	61.3 ±0.8 (6.13% v/v)
Particle Size Distribution (PSD)	% (w/w)	Sand 76.32; Silt 9.91; Clay 13.77
Particle density (ρp)	gcm^{-3}	2.69±0.06
Bulk density (ρb)	gcm^{-3}	1.23±0.07
pH	a.u.	7.096±0.01
Electrical Conductivity (EC)	dSm^{-1}	0.43±0.09
Porosity (θ)	%	54.2
Soil water holding capacity	mmm^{-1}	**62.7**±0.2 (6.27% v/v)
Residual water content (θ_r)	mmm^{-1}	**58.27**
Saturated water content (θ_s)	mmm^{-1}	**474.14**
Volumetric water at saturation	mmm^{-1}	**542.4**
Land preparation	a.u.	Single primary tillage using rotavator; depth of cut 20 cm

Note. Soil moisture values are expressed as volumetric water content (mmm^{-1}), representing the depth of water (mm) per unit depth of soil (mm).

management to minimize water losses and maintain adequate moisture within the root zone. These soil conditions reinforce the relevance of evaluating automated irrigation strategies for improving water-use efficiency under semi-arid conditions.

3.2. Typical Root Growth Distribution of Brinjal in Sandy Loam Soil

Figure 2 illustrates the typical root development pattern of brinjal in sandy loam soil, consistent with the conditions of the experimental field, as reported by Manikandan and Ravikumar (2020). During the vegetative stage, root depth is generally limited to 10–15 cm, indicating the importance of maintaining a shallow wetted zone near the emitter. As the crop progresses to the flowering and fruiting stages, root depth extends to 25–50 cm, with lateral spread reaching up to 35 cm.

This pattern suggests that root growth adapts to the geometry of the wetted bulb created by drip irrigation, highlighting the influence of soil texture and irrigation frequency on root zone development. These observations are consistent with the measured soil properties (Table 2), where high infiltration and moderate water retention promote deeper water movement and vertical root expansion (Hillel, 2004).

3.3. Observed Root Distribution of Brinjal in the Experimental Field

The reference study provides a conceptual baseline for interpreting root growth under the Automated Drip Irrigation Treatment (ADIT) configuration and Manual Drip Irrigation Treatment (MDIT) configuration. The observed vertical root distribution in the experimental field is presented in Figure 3. Root depth increased progressively from the vegetative to the fruiting stage, reaching a mean depth of approximately 35 cm. This is lower than the 50 cm depth reported under unconstrained sandy loam conditions (Manikandan & Ravikumar, 2020; Figure 3), indicating restricted vertical root development.

The restricted vertical root development observed in the field may be associated with the presence of a compacted subsurface layer encountered during root excavation at approximately 30 cm depth. However, penetration resistance and layer thickness were not directly quantified during the study. Therefore, its influence on treatment responses cannot be separated from that of the irrigation configurations. Such layers impose mechanical resistance to root penetration, even under adequate moisture and aeration conditions (Bengough et al., 2006; Hamza & Anderson, 2005). As a result, roots tend to proliferate laterally above the compacted layer and exhibit morphological adaptations such as thickened root tips (Kumar et al., 2021). Mean root spread was 40.7±3.3 cm under ADIT configuration and 33.0±4.1 cm under MDIT configuration. Descriptive analysis based on measurements from 15 plants per treatment indicated an observable difference between

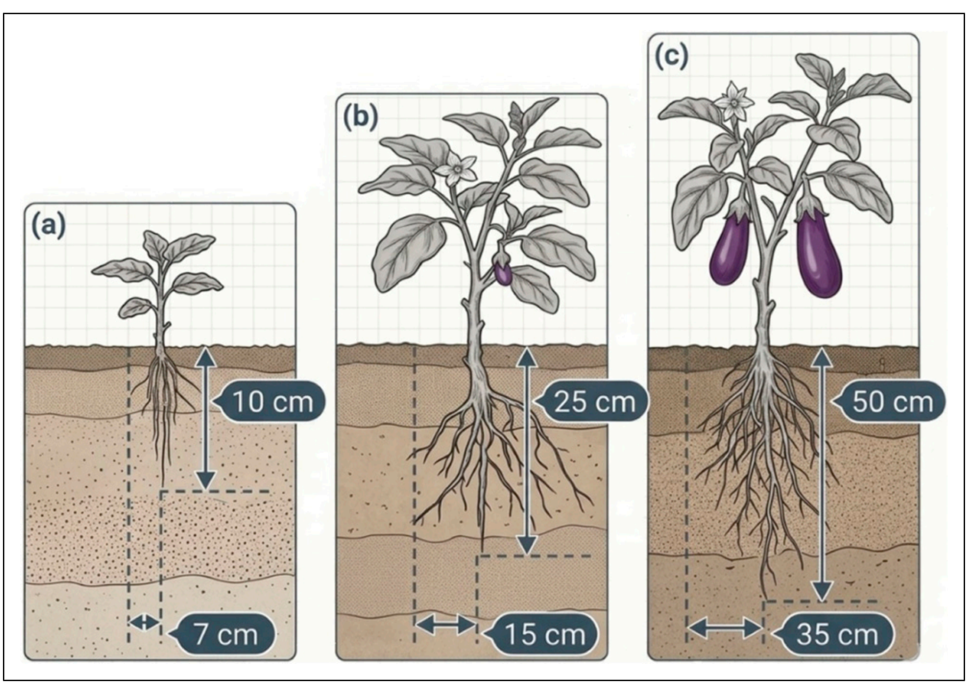

Figure 2. Maximum root distribution along (a) Vegetative growth stage, (b) 50% Flowering stage, and (c) Bearing stage of brinjal (adapted root distribution from Manikandan, M. and Ravikumar, V. (2020))

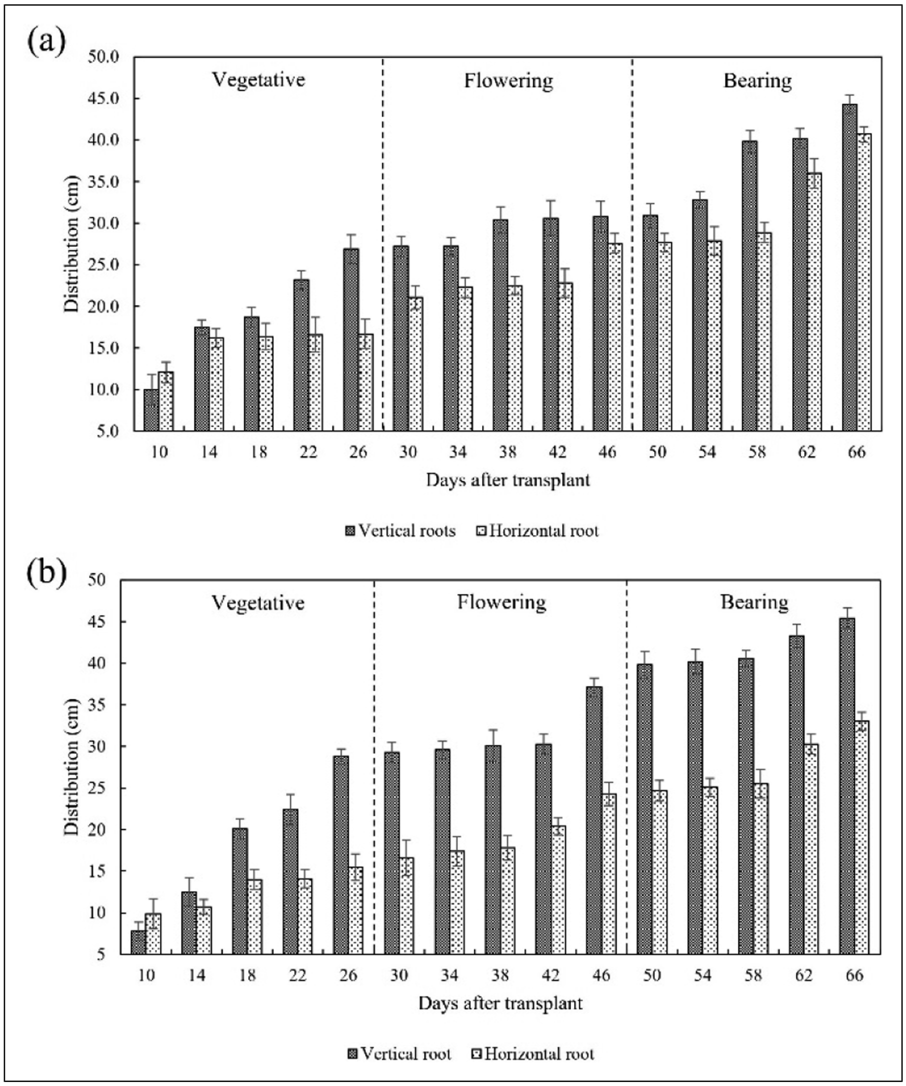

Figure 3. Vertical and horizontal root distribution of brinjal plants under (a) the Automated Drip Irrigation Treatment (ADIT) and (b) the Manually Operated Drip Irrigation Treatment (MDIT). Measurements were obtained from field observations at 4-day sampling intervals throughout the crop growth period. Horizontal and vertical root spread are expressed in centimeters (cm). Each represents measurements from 15 sampled plants per treatment (n = 15)

treatments, as shown in Figure 3. These observations were derived from sampled plants within the respective treatment plots and are presented descriptively because the experimental design did not include replicated treatment plots required for inferential comparison. This difference is primarily attributed to the higher emitter flow rate in ADIT configuration (8 L h^{-1}), which promotes more uniform and sustained soil moisture conditions near field capacity. In contrast, the lower flow rate in MDIT configuration (4 L h^{-1}) results in intermittent wetting and drying cycles, potentially reducing oxygen diffusion in the rhizosphere and limiting lateral root expansion (Bengough et al., 2006; Hillel, 2004; Liu et al., 2015;).

This observation may be associated with differences in irrigation application characteristics, including emitter discharge, irrigation management strategy, and resulting soil moisture distribution. However, because the irrigation configurations also differed in several hydraulic characteristics and the study was conducted using single operational treatment plots, these observations should not be interpreted as evidence of a causal effect of automation alone. In both treatments, the hardpan restricted vertical root penetration and redirected growth laterally. However, the automated system maintained a more favorable soil moisture regime, supporting greater lateral expansion within the confined root zone. These findings highlight the combined influence of soil physical constraints and irrigation management on root system architecture and water-use dynamics in brinjal.

3.4. Effects of Irrigation Treatments on Soil Moisture Dynamics

3.4.1. Soil Moisture Saturation From 50% Depletion

Although both treatments applied the same total daily irrigation volume (8 L plant^{-1}), the application rates differed (Table 1), resulting in distinct soil moisture dynamics and root-zone responses. Figure 4 illustrates the temporal and spatial distribution of soil moisture under the Automated Drip Irrigation Treatment (ADIT) and Manual Drip Irrigation Treatment (MDIT) configurations.

Soil moisture was monitored using a digital tensiometer. The instrument records soil water tension and incorporates a manufacturer-provided conversion relationship to estimate volumetric soil moisture content (%). Measurements were collected from two monitoring locations within each subplot at 10-minute intervals during irrigation events, and average values were used for subsequent analysis. From the 50% depletion level, ADIT configuration achieved soil saturation significantly faster (≈80 min) than MDIT (≈270 min). This difference is attributed to the higher emitter flow rate in ADIT (8 L h^{-1}), which promoted more rapid horizontal advancement of the wetting front. In contrast, the lower flow rate in MDIT configuration (4 L h^{-1}) resulted in slower wetting and extended irrigation duration, limiting lateral moisture spread and increasing the likelihood of moisture loss under the high saturated hydraulic conductivity (198.7 mm day^{-1}) of the soil (Section 3.1).

During the initial phase of irrigation (first 30 min), both treatments reached similar volumetric water content (~57%) within the root zone despite differences in flow rate. This reflects the dominance of soil infiltration capacity during early wetting, when unsaturated conditions and larger pore spaces in sandy loam soils allow rapid water intake (Jury and Horton (2004). Beyond this initial stage, ADIT configuration exhibited a more rapid increase in soil moisture, approaching field capacity more quickly due to its higher application rate. At this stage, gravitational flow begins to dominate over capillary forces, influencing downward water movement and redistribution within the soil profile (Liu et al., 2015). Understanding initial saturation conditions was essential to interpret the subsequent depletion and redistribution of moisture in the soil profile. These results highlight the importance of irrigation application rate in controlling wetting front development and soil moisture distribution, particularly in coarse-textured soils where rapid infiltration can influence water availability and potential losses.

3.4.2. Soil Moisture Depletion

The temporal variation of soil moisture following irrigation showed distinct depletion patterns across brinjal growth stages (Figure 5). During the vegetative stage, moisture depletion was relatively gradual and similar under both treatments. However, during the flowering and fruiting stages, the rate of depletion increased, and the time required to reach 50% depletion of available soil water between field capacity (FC) and permanent wilting point (PWP) decreased progressively.

This trend can be attributed to increased evapotranspiration and root activity as the crop matures. Higher crop coefficients (Kc ≈ 1.08), increased leaf area index, greater stomatal activity, and fruit development collectively enhance water demand and accelerate soil moisture extraction (Allen et al., 1998; Hillel, 2004). In addition, the expanding root system increases the effective root zone volume, further intensifying water uptake (Manikandan & Ravikumar, 2020).

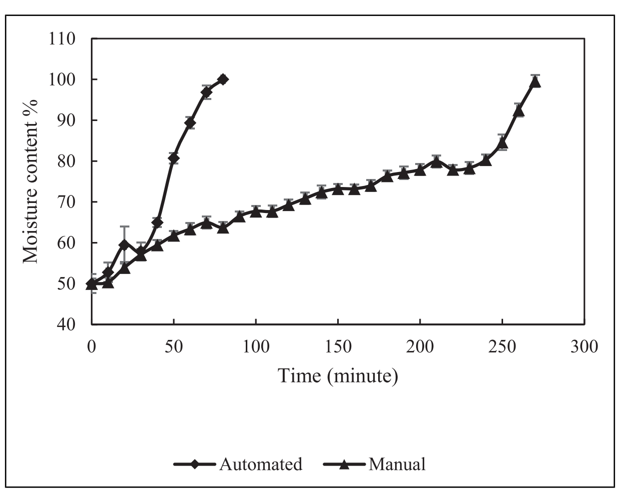

Figure 4. Soil moisture saturation curves showing the increase in volumetric water content (%) with time following irrigation in sandy loam soil under the Automated Drip Irrigation Treatment (ADIT) and the Manually Operated Drip Irrigation Treatment (MDIT). Values represent the mean of measurements obtained from multiple monitoring locations within the experimental plots (n = 6 observations per time interval). Error bars = ± SD

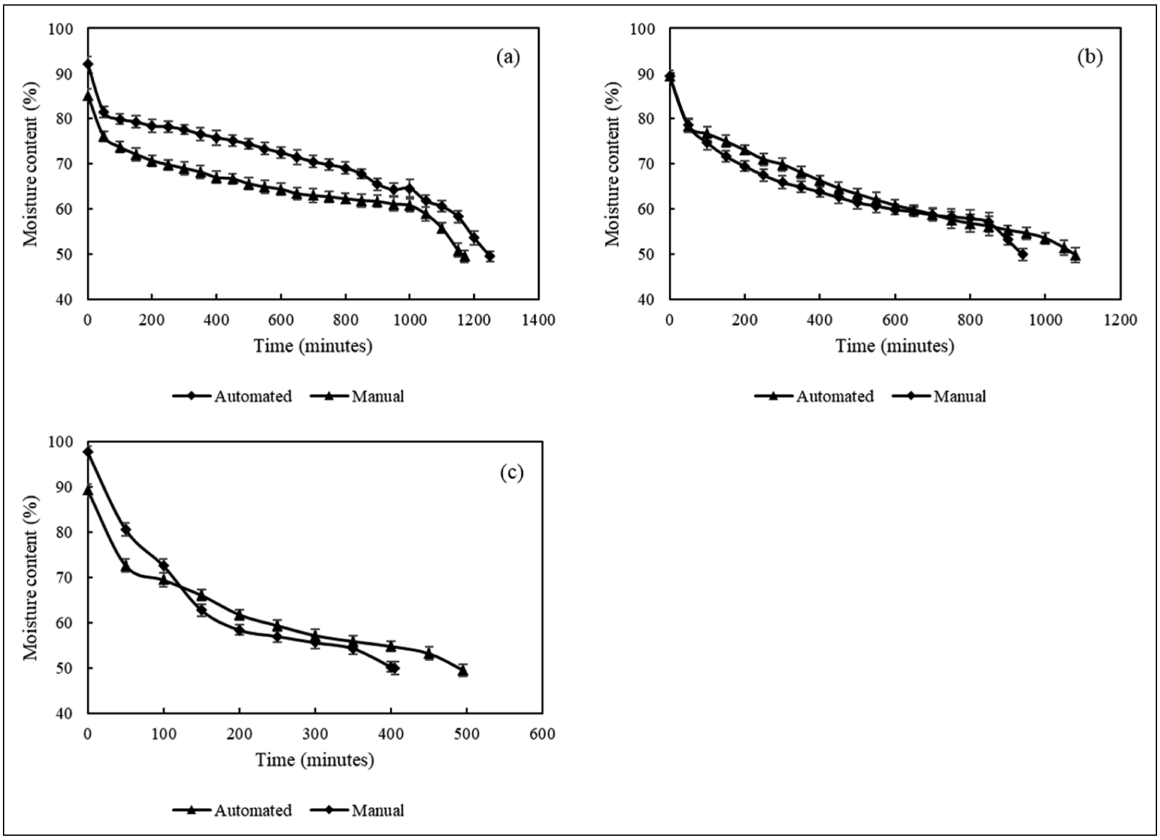

Figure 5. Soil moisture depletion curves showing changes in volumetric water content (%) under the Automated Drip Irrigation Treatment (ADIT) and the Manually Operated Drip Irrigation Treatment (MDIT) during the (a) vegetative, (b) flowering, and (c) bearing growth stages of brinjal. Values represent mean field measurements obtained from multiple monitoring locations within each treatment (n = 6 observations/interval). Error bars = ± SD

Soil properties also influenced the depletion patterns. The relatively high saturated hydraulic conductivity (198.7 mm day^{-1}) and moderate available water capacity (62.7 ±0.2 mm m^{-1}) facilitated rapid drainage and reduced resistance to plant water uptake (Hillel, 2004; Weil & Brady, 2017). As a result, faster moisture decline was observed after irrigation, particularly during later growth stages.

Despite similar overall trends, the Automated Drip Irrigation Treatment (ADIT) configuration exhibited more consistent depletion curves and slightly longer moisture retention compared to the Manual Drip Irrigation Treatment (MDIT) configuration (Figure 5). This can be attributed to the higher application rate (8 L h^{-1}) and more stable wetting patterns under ADIT, which reduce wetting-drying fluctuations and help maintain favorable soil matric potential (Cahn & Johnson, 2017).

3.5. Crop Water Analysis Under Irrigation Management

3.5.1. Crop Water Requirement (CWR)

Crop evapotranspiration (ETc), estimated using the FAO CROPWAT model (version 8.0), showed a progressive increase from the vegetative to the fruiting stages of brinjal (Figure 6). This trend reflects the combined effects of increasing crop coefficient (Kc) and canopy development (Allen et al., 1998). During the early vegetative stage (up to 26 days after transplanting, DAT), ETc ranged from 3.6 to 4.2 mm day^{-1}, indicating moderate evaporative demand associated with limited leaf area. As the crop entered the flowering stage (26–48 DAT), ETc increased to approximately 5.4 mm day^{-1}, driven by rapid canopy expansion, enhanced stomatal activity, and higher metabolic demand (Hillel, 2004). Peak ETc values exceeding 6.0 mm day^{-1} were observed during the fruiting stage (48–60 DAT), corresponding to maximum canopy development (≈9881 cm^{2}). Reference evapotranspiration (ETo) during the study period ranged from 5.55 to 6.99 mm day^{-1}, indicating relatively high atmospheric evaporative demand. The observed ETc values followed seasonal changes in ETo and crop development stages.

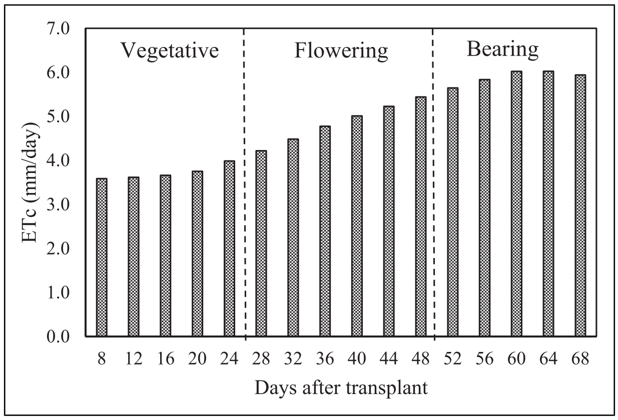

Figure 6. Estimated crop water requirement (CWR, mm day^{-1}) of brinjal at different growth stages, calculated using the FAO CropWat model based on the experimental conditions. Values represent deterministic model outputs and therefore measures of variability are not applicable

Following the peak fruiting period, ETc declined slightly (maximum observed value: 6.02 mm day^{-1}), reflecting reduced physiological activity and fruit development. The expansion of the root system during later growth stages increased the effective water-absorbing area, supporting higher transpiration rates in response to atmospheric demand (ETo).

The observed ETc pattern identifies the fruiting stage as the most critical period for crop water requirement under semi-arid conditions in Kilinochchi, Sri Lanka. These values are consistent with previously reported ranges for brinjal grown in sandy loam soils (Manikandan & Ravikumar, 2020).

Furthermore, the ETc dynamics align with the Soil-Plant-Atmosphere Continuum (SPAC) concept, where water flux is governed by interactions among soil moisture availability, root distribution, and atmospheric demand (Hsiao et al., 2007; Kramer & Boyer, 1995). The sandy loam soil, characterized by high hydraulic conductivity (198.7 mm day^{-1}) and moderate field capacity (12.4% v/v; Section 3.1), promotes rapid water movement and aeration but also leads to faster depletion of soil moisture (Weil & Brady, 2017). As a result, crop water demand becomes highly sensitive to irrigation management. This explains the improved soil moisture regulation observed under the automated irrigation system (Section 3.4), which better maintained optimal moisture conditions within the root zone.

3.5.2. Total Water Requirement (TWR)

Total water requirement (TWR), defined as the sum of net water requirement (NWR) and soil water losses (including deep percolation and evaporation within the effective root zone), exhibited a decreasing trend from the vegetative to the fruiting stage under both Automated Drip Irrigation Treatment (ADIT) and Manual Drip Irrigation Treatment (MDIT) configurations (Figure 7).

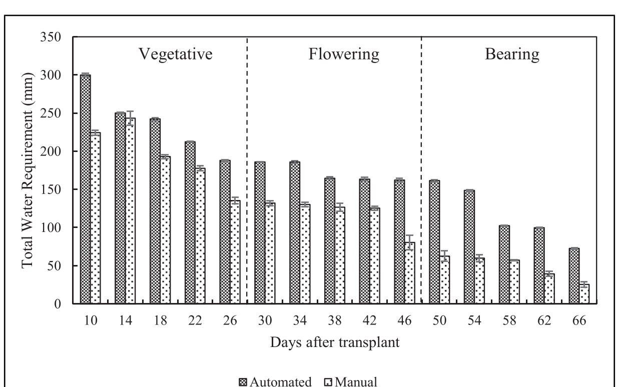

Figure 7. Comparison of estimated total water requirement (TWR, mm) between the Automated Drip Irrigation Treatment (ADIT) and the Manually Operated Drip Irrigation Treatment (MDIT) throughout the brinjal growing period. TWR values were calculated from the experimental water balance and model-derived estimates

Although the applied irrigation depth per event remained constant across growth stages, TWR varied due to changes in soil-plant interactions, particularly root zone development. During the early vegetative stage (10–26 DAT), TWR was highest, reaching 299.85 mm under ADIT configuration and 224.4 mm under MDIT configuration. This is primarily attributed to the shallow root system (≈7–10 cm; Section 3.3), which limits water uptake and increases deep percolation losses in sandy loam soil (Section 3.1; (Hillel, 2004).

At this stage, a significant portion of applied water moved beyond the effective root zone due to limited root depth, reducing water-use efficiency. As the crop progressed to flowering and fruiting stages, TWR decreased despite the increase in crop evapotranspiration (ETc) (Section 3.5.1). This inverse relationship reflects improved water uptake efficiency associated with root system expansion, which allows greater utilization of soil moisture within the wetted zone and reduces percolation losses.

Consequently, TWR declined to below 100 mm during the later fruiting stage, even when ETc reached its peak. Similar trends have been reported for brinjal grown in sandy loam soils, where maturing root systems reduce water losses and improve water-use efficiency (Manikandan & Ravikumar ,2020). These findings indicate that irrigation scheduling is particularly critical during early growth stages, when a substantial fraction of applied water is lost to deep percolation. Optimizing irrigation timing and application rates during this period is essential to improve water productivity under semi-arid conditions.

3.5.3. Net Water Requirement (NWR)

The stage-wise variation of net water requirement (NWR) is presented in Figure 8, showing a progressive increase from the vegetative to the fruiting stage. NWR represents the volume of water required to replenish the soil moisture deficit within the effective root zone up to field capacity (FC) after depletion due to evapotranspiration. It is primarily governed by root zone depth and soil properties, including FC, permanent wilting point (PWP), and bulk density (ρb) (Section 3.1; Table 2).

The increasing trend in NWR reflects the expansion of the root zone, greater biomass accumulation, and higher transpiration demand associated with canopy and fruit development (Allen et al., 1998). During the early vegetative stage (10–26 DAT), NWR remained relatively low (38.6–103.7 mm) due to limited leaf area and lower evapotranspiration. As the crop advanced to flowering and fruiting stages, NWR increased progressively, exceeding 160 mm by 60 DAT, consistent with the higher ETc values observed in Section 3.5.1.

Despite differences in irrigation application rates between treatments, NWR values were similar for both systems at each growth stage. This is expected, as NWR reflects soil moisture deficit within the root zone and is independent of water losses such as deep percolation and evaporation (Weil & Brady, 2017).

These results highlight the importance of synchronizing irrigation scheduling with crop water demand. Efficient irrigation management should aim to minimize water losses during early growth stages while ensuring adequate moisture supply during peak demand periods. The comparison with CWR and TWR indicates that a substantial portion of applied water is lost, particularly during early growth, emphasizing the need for improved irrigation strategies under semi-arid conditions.

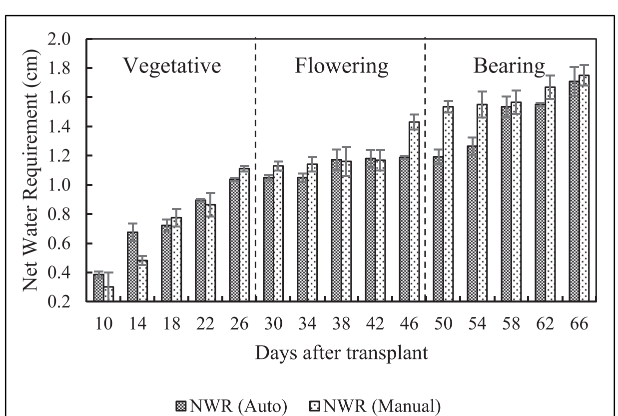

Figure 8. Estimated net water requirement (NWR, mm) of brinjal under the Automated Drip Irrigation Treatment (ADIT) and the Manually Operated Drip Irrigation Treatment (MDIT) from the vegetative to bearing growth stages. Values were calculated from CropWat-based irrigation scheduling and represent deterministic estimates; therefore, measures of variability are not presented

3.6. Analysis of Wetting Front Formation

3.6.1. Wetting Pattern Analysis Under ADIT

Figure 9 presents the simulated wetting front under the Automated Drip Irrigation Treatment (ADIT) configuration across different growth stages of brinjal. HYDRUS-1D simulations were conducted using an adaptive time-stepping procedure, allowing the numerical solver to automatically adjust computational time steps according to convergence requirements during simulation. Contour lines represent volumetric water content (cm^3 cm^{-3}) following a 30 min irrigation event, while dashed lines indicate the maximum observed root distribution at each stage. Although the simulated wetting patterns showed strong agreement with observed surface wetting-width measurements ($R^2 = 0.91$), subsurface wetting-front development was not directly validated under field conditions. Consequently, the simulated wetting-front distributions should be interpreted as model-based representations of relative treatment behavior rather than exact field measurements.

The simulations show that variations in wetting front advancement immediately after irrigation were minimal (<0.2%) across growth stages, reflecting the dominant influence of soil hydraulic properties over root water uptake during the initial phase. Noticeable differences in moisture distribution emerged several hours after irrigation, as root water uptake and root zone expansion became more influential.

Following a 30 min irrigation pulse, the wetting front extended to approximately 36 cm vertically and 38 cm radially, with volumetric water content ranging from 0.35 to 0.42 cm^3 cm^{-3}. During the vegetative stage, the average root zone (≈22.9 × 33.2 cm) was fully encompassed within the wetted volume. However, significant downward water movement beyond the root zone was observed, indicating deep percolation losses. This behavior is consistent with the high saturated hydraulic conductivity (198.7 mm day^{-1}) and low organic matter content (1.21%) of the soil (Section 3.1), and explains the elevated TWR reported in Section 3.5.2.

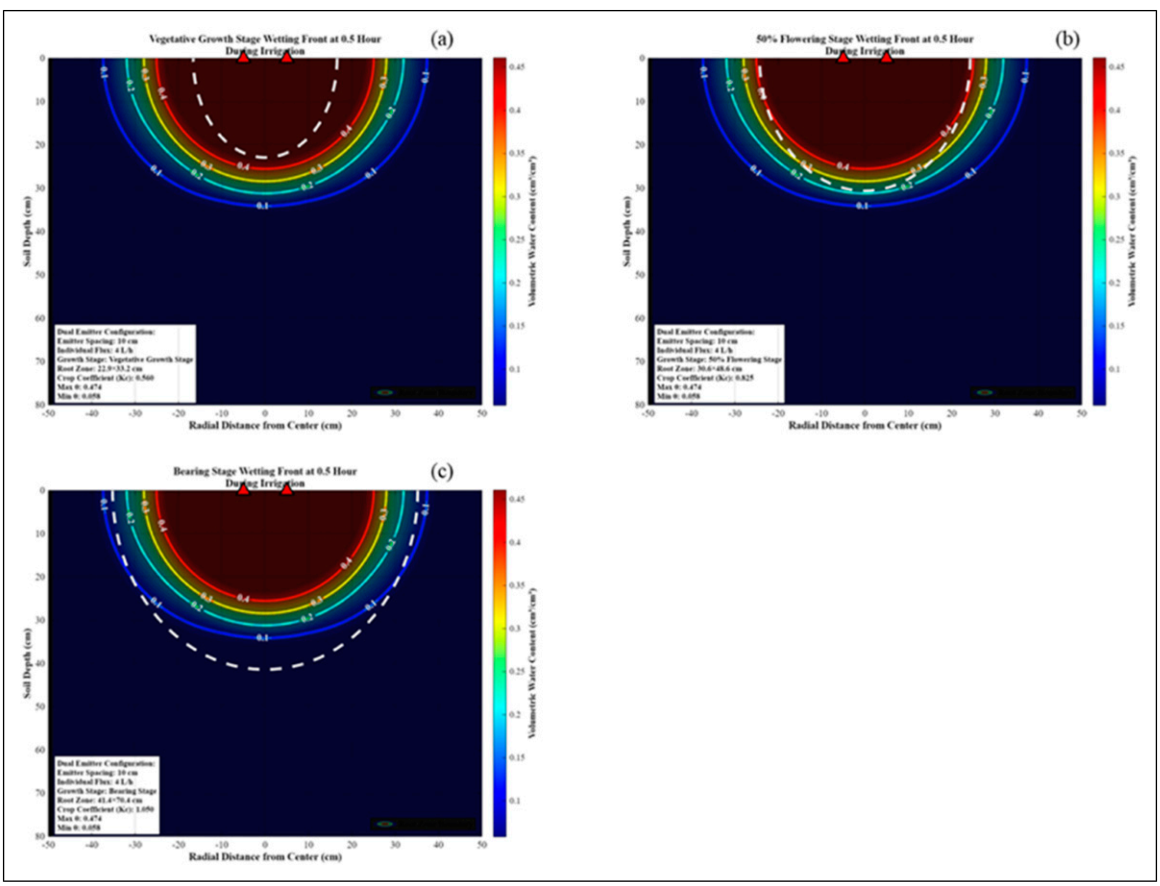

Figure 9. MATLAB-generated contour plots illustrating simulated soil wetting patterns and representative root-zone distribution under the Automated Drip Irrigation Treatment (ADIT) during different brinjal growth stages. The contour plots were developed using volumetric water content outputs generated by the HYDRUS-1D model. Contours represent simulated volumetric water content (%)

As the crop progressed to the flowering stage, the root zone expanded (≈30.6 × 48.6 cm), occupying a larger proportion of the wetted volume (∼54%). This reduced downward water flux beyond the root boundary and improved moisture retention within the effective root zone. During the fruiting stage, the root system further expanded (≈41.4 × 70.4 cm), extending beyond the initial wetting front generated by the 30 min irrigation event. Consequently, the applied irrigation volume became insufficient to fully meet root zone demand, indicating a mismatch between irrigation depth and root development.

HYDRUS-1D simulations suggested that deep percolation below the effective root zone could account for approximately 35–40% of applied water under MDIT, whereas considerably lower deep percolation losses (<10% of applied water) were predicted under ADIT configuration. These values represent model-derived estimates rather than direct field measurements.

These results highlight that a constant irrigation duration (30 min; ∼4.0 L $plant^{-1}$) results in variable water-use efficiency across growth stages. During the vegetative stage, excess water application led to percolation losses of up to ∼40%. Reducing irrigation duration to approximately 18 – 20 min (∼2.5 L $plant^{-1}$) would better match the limited root zone and soil water demand at this stage.

During the flowering stage, the wetting front closely matched root distribution, suggesting that the existing irrigation duration is adequate to maintain near-field-capacity conditions without inducing significant losses. In contrast, during the fruiting stage, the wetting front covered approximately 85% of the root zone, indicating a deficit. Increasing irrigation duration by ∼15% (to ∼35 min; ∼4.6 L $plant^{-1}$) would improve moisture coverage and support optimal crop water uptake.

The presence of a compacted subsurface layer at ∼30 cm depth further influences water distribution by limiting vertical percolation and promoting lateral spread (Hamza & Anderson, 2005). This condition enhances the effectiveness of increased irrigation volumes during later growth stages by retaining water within the root zone.

Overall, these findings demonstrate that stage-specific adjustment of irrigation duration, aligned with root development and evapotranspiration demand, can significantly improve soil moisture regulation and water-use efficiency under automated drip irrigation systems.

3.6.2. Wetting Pattern Analysis Under MDIT

Figure 10 illustrates the simulated wetting front under the Manual Drip Irrigation Treatment (MDIT) configuration, showing distinct spatial and temporal differences in soil moisture distribution compared to the automated system. A 30 min simulation represents the midpoint of a typical 60 min irrigation event, corresponding to approximately 2 L of water applied per plant.

After 30 min of irrigation, the wetting front covered an area of approximately 1151 cm^2, with a vertical reach of 25 cm and a radial spread of 23.2 cm from the emitter. Similar to ADIT configuration, initial wetting front advancement varied by less than 0.2% across growth stages, indicating that early infiltration is primarily governed by soil hydraulic properties rather than root water uptake.

During the vegetative stage, the average root zone (≈23.8 × 29.0 cm) occupied more than 60% of the wetted area. Unlike ADIT configuration, deep percolation below the root zone was minimal, as volumetric water content decreased to below 0.20 $cm^3\ cm^{-3}$ near the lower boundary of the wetting front. However, lateral redistribution of water was more pronounced, with an estimated ∼35% of applied water moving beyond the active rhizosphere. This suggests that slower application rates promote horizontal spreading but may reduce effective water availability within the root zone (Hsiao et al., 2007).

At the flowering stage, root expansion (≈32.5 × 41.6 cm) resulted in approximately 85% coverage of the root zone by the wetting front after 30 min. However, lower volumetric water content (<0.10 $cm^3\ cm^{-3}$) in parts of the root zone indicates incomplete wetting at this stage. Although the full 60 min irrigation cycle improves vertical infiltration (Section 3.4.2), the 30 min pattern reveals a pronounced moisture gradient between surface and mid-depth layers.

During the fruiting stage, the root system expanded further (≈43.1 × 59.2 cm), while the 30 min wetting front covered only about 70% of the root zone. Lower moisture levels (0.10–0.25 $cm^3\ cm^{-3}$) in deeper layers suggest that even extended irrigation duration may not fully satisfy crop water demand under this system.

Irrigation performance indicators further highlight these limitations. The automated system achieved higher uniformity (EU: 90 – 92%, CU: 91 – 93%, DU: ∼88%) compared to the manual system (EU: 78 – 82%, CU: 75 – 80%, DU: ∼72%), reflecting more consistent water distribution. The lower performance of MDIT configuration is attributed to temporal pressure variations and uneven discharge during longer irrigation events (Howell, 2001; Phogat et al., 2013).

Deep percolation estimates presented in this study were derived exclusively from HYDRUS-1D simulations and were not directly measured under field conditions. Although simulated surface wetting widths showed good agreement with field observations (R^2 = 0.91), independent validation of subsurface water movement and deep percolation was not feasible without disturbing the experimental plots. Consequently, the reported percolation losses should be interpreted as model-derived estimates that provide insight into likely water movement patterns rather than direct measurements of field conditions.

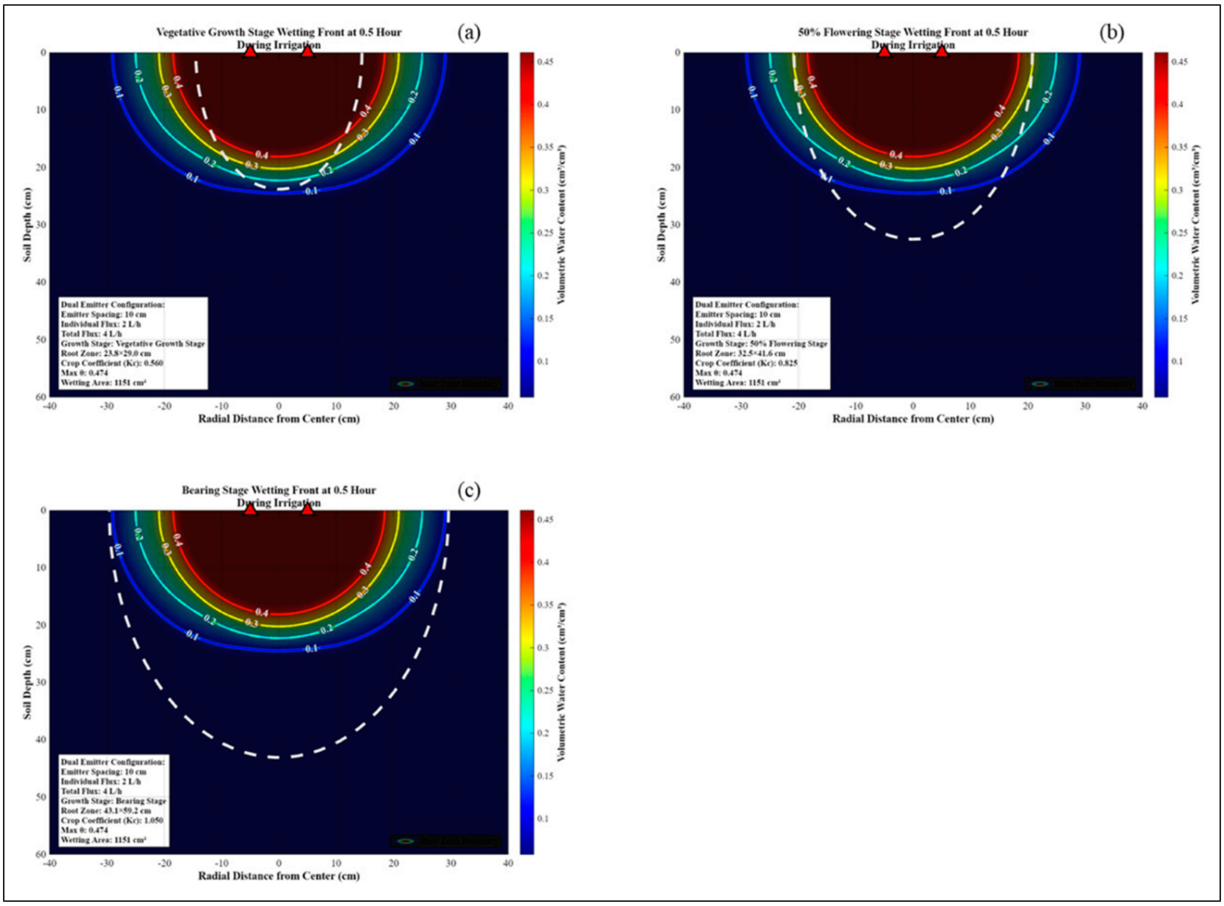

Figure 10. MATLAB-generated contour plots illustrating simulated soil wetting patterns and representative root-zone distribution under the Manually Operated Drip Irrigation Treatment (MDIT) during different brinjal growth stages. The contour plots were developed using volumetric water content outputs generated by the HYDRUS-1D model. Contours represent simulated volumetric water content (%)

Overall, the results indicate that the manual system provides less uniform and less effective wetting of the root zone, particularly at later growth stages. This limitation reduces water-use efficiency and highlights the advantages of automated irrigation in maintaining optimal soil moisture conditions under coarse-textured soils.

3.6.3. Comparison With Previous Irrigation Automation Studies

The findings of the present study are generally consistent with previous investigations demonstrating that Automated Drip Irrigation Treatment (ADIT) configuration can improve irrigation water-use efficiency and maintain more favorable soil moisture conditions than conventional manually scheduled irrigation. Sensor-controlled irrigation systems in vegetable production have been reported to reduce unnecessary irrigation applications while maintaining crop productivity through irrigation events triggered by soil moisture conditions rather than fixed schedules (Sharma et al., 2021). Similarly, automated irrigation systems have been shown to improve water productivity in broccoli and other vegetable crops compared with manually operated irrigation practices.

Unlike most previous studies, however, the present investigation evaluated a practical field-scale time-based automated irrigation configuration rather than a continuously sensor-controlled system (Vallejo-Gómez et al., 2023). Although sensor-based irrigation generally provides greater adaptability to changing soil moisture conditions, time-based automation offers a simpler and more economical alternative that may be more suitable for smallholder production systems where equipment cost, maintenance, and technical expertise are important considerations. The present results suggest that such simplified automation can still improve irrigation management under field conditions, although the magnitude of these improvements will depend on local soil and climatic conditions (Kaptein et al., 2019).

It should also be recognised that many previous automation studies compared irrigation controllers using hydraulically identical irrigation systems, thereby isolating the effect of the control strategy. In contrast, the present study compared two complete operational irrigation configurations that differed in both automation and hydraulic characteristics. Consequently, the observed improvements in soil moisture dynamics, root development, and irrigation water-use efficiency should be interpreted as comparative field performance of the evaluated irrigation configurations rather than the isolated effect of automation alone. Future replicated studies employing hydraulically identical systems would enable clearer separation of controller effects from hydraulic design characteristics.

3.7 Yield and Water Productivity in Semi-arid Brinjal Cultivation

The yield performance of brinjal (*Solanum melongena* L.) under different irrigation strategies has been widely documented in semi-arid agroecosystems. Conventional surface or furrow irrigation systems typically result in moderate yields (≈12 – 18 t ha^{-1}) under farmer-managed conditions, often associated with high seasonal water applications (>700 mm) and substantial losses due to evaporation, runoff, and non-uniform water distribution (Shivani et al., 2019; Singandhupe et al., 2007). These limitations highlight the need for more efficient irrigation approaches under increasing water scarcity.

Drip irrigation systems, particularly when combined with plastic mulch, have consistently demonstrated improved yield and water productivity. Previous studies report yield increases of approximately 7.6 – 10.9% over surface irrigation, alongside reductions in irrigation depth and improved water-use efficiency (Singandhupe et al., 2016). Similarly, drip–mulch systems have achieved yields in the range of 17 – 22 t ha^{-1} under semi-arid conditions, depending on soil properties and management practices.

Marketable fruits were harvested periodically throughout the production season, and the cumulative harvested yield from each irrigation configuration was recorded. Yield is presented both as area-normalized productivity (t ha^{-1}), representing crop productivity per unit cultivated area, and as average yield per plant (kg plant^{-1}) to facilitate comparison between irrigation configurations that differed in total plot size and plant population. The reported yield values should therefore be interpreted as configuration-level field observations obtained under the experimental conditions of the present study.

In the present study, the Manual Drip Irrigation Treatment (MDIT) configuration, which applied a fixed irrigation depth of 8 L plant^{-1} day^{-1} under mulch, produced a yield of 16.7 t ha^{-1}. This value falls within the upper range reported for conventional drip-mulch systems, indicating that baseline agronomic and soil conditions were favorable. In contrast, the Automated Drip Irrigation Treatment (ADIT) configuration achieved a yield of 22.3 t ha^{-1} under the same total water input, representing a 33.5% increase over MDIT configuration. When expressed on a per-plant basis, average yield was 2.35 kg plant^{-1} under ADIT configuration and 1.62 kg plant^{-1} under MDIT configuration. The approximately 45% higher per-plant yield observed under ADIT configuration suggests that the greater treatment productivity was not solely attributable to differences in plant population between plots. This performance places ADIT configuration at the upper bound of productivity reported for drip-irrigated brinjal in semi-arid environments.

The yield advantage under ADIT configuration is comparable to outcomes from precision irrigation studies, where optimized water and nutrient delivery can produce yields exceeding 20 t ha^{-1}. Although higher yields (up to ~37.9 t ha^{-1}) have been reported under controlled fertigation regimes (Gevariya et al., 2025), such systems often involve intensive nutrient management. In contrast, the results obtained here under open-field conditions highlight the practical effectiveness of time-based irrigation automation.

Water productivity metrics further reinforce the comparative advantage of ADIT configuration. Water productivity further emphasizes the benefits of automation. Irrigation water-use efficiency (IWUE) under ADIT configuration reached 4.91 kg m^{-3}, representing a 45.7% increase compared to MDIT configuration (3.37 kg m^{-3}). Similar improvements in water productivity have been reported in studies evaluating drip irrigation systems for vegetable crops, where precise water application contributed to higher yields per unit of irrigation water applied (Çolak et al., 2017). These findings are consistent with previous studies indicating that well-managed drip systems can significantly improve water productivity while reducing total water use (Singandhupe et al., 2016). In this study, seasonal irrigation depth under ADIT configuration was approximately 454 mm, substantially lower than the 700–900 mm typically reported for surface irrigation systems.

It should be noted that the ADIT and MDIT configurations differed not only in irrigation management approach but also in certain hydraulic characteristics, including pump capacity and emitter discharge rate. Therefore, the observed differences in crop performance cannot be attributed exclusively to automation. Rather, the results reflect the combined influence of the irrigation configurations evaluated under field conditions. Future studies employing hydraulically identical systems would be useful for isolating the specific contribution of automation to treatment performance.

The observed yield gains under ADIT configuration were not driven by increased water input, but by more consistent maintenance of soil moisture between irrigation supply and crop water demand, enhanced soil moisture stability, and higher hydraulic uniformity within the target root-zone range. These factors reduced moisture stress and minimized wetting–drying cycles within the root zone, thereby improving crop performance.

Overall, the automated drip irrigation system demonstrated a clear advantage in achieving higher yields with lower water inputs, positioning it within a high-yield, water-efficient production framework. This makes it particularly suitable for climate change adaptation and sustainable water management in semi-arid agroecosystems, where water scarcity is a critical constraint (Shivani et al., 2019; Singandhupe et al., 2016). The present study focused on agronomic and water-use performance indicators and did not include a detailed economic evaluation of system installation costs, operating expenses, or payback periods. Future studies should integrate economic analyses to assess the financial feasibility of automated drip irrigation systems under commercial production conditions.

3.8 Novelty, Contribution, and Future Perspectives

This study provides a comprehensive field-scale evaluation of a time-based automated drip irrigation system combined with plastic mulch, offering new evidence of its effectiveness in improving yield and water productivity in semi-arid brinjal cultivation. While previous research has extensively examined drip irrigation and mulching as separate interventions, the role of simple time-based automation in irrigation scheduling remains underexplored under open-field conditions.

The key novelty lies in demonstrating that automation of irrigation timing operated using predefined irrigation schedules, while soil moisture sensing was used as a supplementary monitoring tool to support irrigation management, can enhance crop performance. The automated system achieved a 33.5% increase in yield and a 45 – 46% improvement in irrigation water-use efficiency compared to a manually operated system receiving the same gross irrigation volume. This finding challenges the prevailing assumption that substantial productivity gains in drip irrigation require advanced sensor-based or feedback-controlled technologies.

In addition, this study integrates hydraulic performance metrics, soil moisture dynamics, wetting patterns, root distribution, and yield responses within a single experimental framework. By linking improvements in irrigation uniformity and soil moisture stability to measurable agronomic outcomes, it provides a mechanistic understanding of how irrigation scheduling influences crop performance.

The yields obtained under automation (22.3 t ha^{-1}) fall within the upper range reported for drip-irrigated brinjal in semi-arid regions, while operating at lower seasonal water inputs than conventional surface irrigation systems. These results position time-based automation, combined with mulching, as a cost-effective, scalable, and climate-resilient irrigation strategy, particularly suitable for small and medium-scale farmers in water-limited environments.

Overall, the study contributes to irrigation science by demonstrating that relatively simple technological interventions focused on scheduling precision can substantially improve water productivity and crop yield, offering a practical pathway for enhancing climate change adaptation and water security in semi-arid agricultural systems.

Future research should focus on enhancing automated irrigation systems through the integration of real-time soil moisture sensing and climate-responsive control algorithms to improve precision water management. Incorporating sensor-based feedback mechanisms, such as capacitance or time-domain reflectometry sensors, would enable dynamic irrigation scheduling based on actual crop water demand rather than fixed time intervals. In addition, Internet of Things (IoT)-enabled platforms and remote monitoring systems could support data-driven decision-making and improve operational efficiency at the farm level.

Long-term studies are needed to evaluate the impacts of automated drip irrigation and polythene mulching on soil health, including changes in soil structure, porosity, and microbial activity. Expanding research across diverse soil types, climatic conditions, and cropping systems would also improve the broader applicability of these findings.

Economic assessments, including cost-benefit analysis and energy-use efficiency, are essential to determine the feasibility of adopting automated irrigation technologies at both smallholder and commercial scales. Furthermore, future work should investigate the integration of automation with deficit irrigation strategies to optimize water savings while maintaining yield stability.

Collectively, these research directions will support the development of climate-resilient, resource-efficient irrigation systems and contribute to sustainable water management in agriculture under increasing climatic variability.

4. Conclusions

This field-scale pilot study compared two operational drip irrigation configurations under polythene mulch for brinjal cultivation in a sandy loam soil under semi-arid conditions. The Automated Drip Irrigation Treatment (ADIT) configuration showed more favorable soil moisture dynamics, greater observed lateral root development, higher irrigation water-use efficiency, and greater area-based and per-plant yield than the Manual Drip Irrigation Treatment (MDIT) configuration under the experimental conditions of the study. Because the evaluated irrigation systems differed in both automation and hydraulic characteristics and the experiment was conducted without replicated treatment plots, these observations should be interpreted as comparative performance of the evaluated irrigation configurations rather than evidence of the isolated effect of automation. The observed performance may have been influenced not only by the automation strategy but also by differences in hydraulic characteristics, including emitter discharge, pump capacity, and irrigation application strategy, which could not be separated within the experimental design.

The sandy loam soil, characterized by high hydraulic conductivity (198.7 mm day^{-1}) and low organic matter (1.21%), facilitated rapid infiltration but increased the risk of deep percolation losses, particularly during early growth stages. Root development in both systems was constrained by a compacted layer at approximately 30 cm depth, promoting lateral root expansion and influencing moisture redistribution within the root zone.

Net water requirement (NWR) increased with crop growth due to expanding root systems and higher transpiration demand, while total water requirement (TWR) decreased from approximately 300 mm during the vegetative stage to below 100 mm at maturity, reflecting reduced percolation losses as root uptake efficiency improved. The ADIT configuration reduced early-stage percolation losses from 35 – 40% to less than 10% at later stages by maintaining more stable soil moisture conditions under the observed climatic conditions.

Water-use efficiency improved progressively, with the automated system achieving higher overall efficiency compared to the manual system due to more frequent and controlled irrigation pulses. These shorter, well-timed applications minimized wetting–drying cycles and maintained favorable soil moisture conditions within the root zone.

Irrigation uniformity was also higher under ADIT configuration (CU: 91 – 93%, EU: 90 – 92%, DU: 88%) compared to the MDIT configuration (CU: 75 – 80%, EU: 78 – 82%, DU: 72%). This improved hydraulic performance contributed directly to enhanced water distribution, reduced localized water stress, and increased yield.

The evaluated automated irrigation configuration demonstrated favorable agronomic performance under the conditions of the present field study. However, because economic factors were not evaluated, further research incorporating installation costs, operating costs, labor requirements, and investment payback analyses is required before conclusions regarding economic feasibility and large-scale adoption can be drawn.

Overall, the automated drip irrigation system combined with mulching proved to be an effective strategy for optimizing soil–water interactions and improving crop productivity under water-limited conditions. The findings suggest that scheduled automated drip irrigation may offer potential benefits for improving irrigation performance and water productivity under conditions similar to those evaluated in the present study.

The findings should be interpreted in light of several study limitations. The investigation was conducted during a single growing season at one field location and involved a field-scale comparison of operational irrigation configurations without replicated treatment plots. In addition, the observed responses may be influenced by the specific soil, climatic, and management conditions of the study site. The HYDRUS-1D simulations were parameterized using soil hydraulic properties estimated through the Rosetta Lite pedotransfer model rather than direct laboratory determination of complete soil water retention characteristics. Furthermore, although simulated surface wetting widths showed good agreement with field observations ($R^2 = 0.91$), direct validation of subsurface wetting patterns was not feasible because excavation of the wetted soil profile during crop growth would have disturbed the root system and compromised the field experiment. Consequently, the simulated soil water distributions should be interpreted as model-based estimates rather than fully validated representations of subsurface water movement. Future studies incorporating direct field validation and formal sensitivity analyses would further strengthen confidence in model predictions. Moreover, the evaluated irrigation systems differed in several operational and hydraulic characteristics, including pump capacity, emitter discharge, irrigation management strategy, and treatment plot dimensions, the observed differences cannot be attributed exclusively to the automation component.

The observed differences between configurations should be interpreted as descriptive field observations rather than statistically validated treatment effects. Although multiple sampling locations and plants were evaluated within each configuration to characterize within-plot variability, these measurements do not constitute independent treatment replicates. Consequently, further multi-season and multi-location studies with replicated experimental designs are recommended to confirm the broader applicability of the findings. Future investigations with hydraulically identical irrigation systems that differ only in the control method are required to isolate the specific contribution of irrigation automation are required to verify the reproducibility of the observed responses and to isolate the contribution of individual irrigation system components.

The present investigation focused on the agronomic and hydraulic performance of the evaluated irrigation configurations. Economic factors, including installation costs, operating costs, maintenance requirements, labor savings, and investment payback period, were not assessed. Consequently, the economic feasibility and scalability of the proposed irrigation configuration cannot be inferred from the present study. Future investigations should incorporate comprehensive techno-economic analyses to complement the agronomic evaluation. Despite these limitations, the automated irrigation configuration maintained more favorable soil moisture conditions, improved irrigation uniformity, and achieved higher water productivity than the manually operated system under the conditions evaluated in this study.

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ORCID iD

Kannan Nadarajah https://orcid.org/0000-0001-8091-589X

Ethical Considerations

This research has no ethical considerations to be considered.

Author Contributions

Maduwantha N. Herath: Writing the original draft, data curation, analysis and methodology, Mayuresh Niranjan: Data analysis, review and editing, Kandiah Pakeerathan: Project administration and drawing of fund, Jameson Arasakesary Sinnathurai: Project administration and drawing of fund, Kannan Nadaraja: Conceptualization, methodology, analysis, review and editing and project administration

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Supplemental Material

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References

AL-agele, H. A., Jashami, H., Nackley, L., & Higgins, C. (2021). A Variable Rate Drip Irrigation Prototype for Precision Irrigation. *Agronomy*, *11*(12), 2493. https://doi.org/10.3390/agronomy11122493

Alexandratos, N. (n.d.). World Agriculture towards 2030/2050: the 2012 revision. https://files/58/Alexandratos-World_Agriculture_towards_20302050_the_2012_revision.pdf

Allan, R., Pereira, L., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56 (Vol. *56*).

Anoop, E. G., & Bala, G. J. (2024). IoT and ML-based automatic irrigation system for smart agriculture system. *Agronomy Journal*, *116*(3), 1187–1203. https://doi.org/10.1002/AGJ2.21344;SUBPAGE:STRING:ABSTRACT;REQUESTEDJOURNAL:JOURNAL:14350645;WEBSITE:WEBSITE:ACSESS.ONLINELIBRARY.WILEY.COM;WGROUP:STRING:PUBLICATION

Aujla, M. S., Thind, H. S., & Buttar, G. S. (2007). Fruit yield and water use efficiency of eggplant (Solanum melongema L.) as influenced by different quantities of nitrogen and water applied through drip and furrow irrigation. *Scientia Horticulturae*, *112*(2), 142–148. https://doi.org/10.1016/J.SCIENTA.2006.12.020

Ayers, R. S., & Westcot, D. W. (2024). *Water quality for agriculture - 6. WATER QUALITY FOR LIVESTOCK AND POULTRY*, 1–5. https://www.fao.org/4/T0234E/T0234E00.htm#TOC

Bengough, A. G., Bransby, M. F., Hans, J., McKenna, S. J., Roberts, T. J., & Valentine, T. A. (2006). Root responses to soil physical conditions; growth dynamics from field to cell. *Journal of Experimental Botany*, *57*(2 SPEC. ISS.), 437–447. https://doi.org/10.1093/JXB/ERJ003

Bethune, M. G., Selle, B., & Wang, Q. J. (2008). Understanding and predicting deep percolation under surface irrigation. *Water Resources Research*, *44*(12), 1–16. https://doi.org/10.1029/2007WR006380

Boninsenha, Í., Rudnick, D. R., Mantovani, E. C., & Ribeiro, H. de Q. (2025). Advancing irrigation uniformity monitoring through remote sensing: A deep-learning framework for identifying the source of non-uniformity. *Agricultural Water Management*, *310*, 109376. https://doi.org/10.1016/j.agwat.2025.109376

Brogowski, Z., Kwasowsky, W., & Madyniak, R. (2015). Calculating particle density, bulk density, and total porosity of soil based on its texture. https://archive.sciendo.com/SSA/ssa.2014.65.issue-4/ssa-2015-0007/ssa-2015-0007.pdf

Shock, C. C., Barnum, J. M., & Seddigh, M.. (1998). Calibration of Watermark Soil Moisture Sensors for Irrigation Management. https://www.researchgate.net/publication/228762944_Calibration_of_W_ermark_Soil_Moisture_Sensors_for_Irrigation_Management

Cahn, M. D., & Johnson, L. F. (2017). New approaches to irrigation scheduling of vegetables. *Horticulturae*, *3*(2), 1–20. https://doi.org/10.3390/horticulturae3020028

Chinthagunti, H., Sarnaik, D. A., & Sharma, D. (2018). Evaluation of Brinjal (Solanum melongena L.) Genotypes for Growth and Yield Parameters. *International Journal of Current Microbiology and Applied Sciences*, *7*(12), 3095–3100. https://doi.org/10.20546/ijcmas.2018.712.354

Dharmasena, P. B. (2011). ResearchGate. https://www.researchgate.net/publication/355186208_Initial_Environmental_Examination_for_Kilinochchi_and_Mullaitivu_Districts_of_Sri_Lanka/link/61658597ae47db4e57ce7962/download?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0a

Dong, Z., Liu, Y., Li, M., Ci, B., Lu, X., Feng, X., Wen, S., & Ma, F. (2023). Effect of different NPK fertilization timing sequences management on soil-petiole system nutrient uptake and fertilizer utilization efficiency of drip irrigation cotton. *Scientific Reports*, *13*(1), 14287. https://doi.org/10.1038/s41598-023-40620-9

Falkenmark, M., & Rockström, J. (n.d.). *The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management Water for Food and Hunger Alleviation*.

Gevariya, S., Marakna, N., Patoliya, B., Kelaiya, S., Ghelani, Y., & Prajapati, G. (2025). BRINJAL (SOLANUM MELONGENA L.) CROP RESPONSE TO FERTIGATION LEVELS UNDER SURFACE AND SUBSURFACE DRIP IRRIGATION. *Plant Archives*, *25*(SI). https://doi.org/10.51470/plantarchives.2025.v25.sp.ictpairs-080

Guo, H., & Li, S. (2024). A Review of Drip Irrigation's Effect on Water, Carbon Fluxes, and Crop Growth in Farmland. *Water (Switzerland)*, *16*(15), 2206. https://doi.org/10.3390/w16152206

Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and Tillage Research*, *82*(2), 121–145. https://doi.org/10.1016/J.STILL.2004.08.009

Hasbi, M., Darma, R., Nawi, N. M., Bakheet Ali, H. N., Maulidyah, N., & Syakur, K. A. (2026). Development of a low-cost timer-based drip irrigation system for sustainable Waxy Corn cultivation in El Niño-Prone regions. *Open Agriculture*, *11*(1), 1–15. https://doi.org/10.1515/opag-2025-0490

Hillel, D. (2004). Introduction to Environmental Soil Physics by Daniel Hillel (z-lib.org). https://books.google.lk/books?hl=en&lr=&id=qK7zzLIUEloC&oi=fnd&pg=PP1&dq=Hillel,+D.+(2004).+Introduction+to+environmental+soil+physics.+Elsevier+Academic+Press.+Lal,+R.+(2020).+Soil+organic+matter+and+water+retention.+Agronomy+Journal,+112(5),+3265–3277.&.

Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, *93*(2), 281–289. https://doi.org/10.2134/agronj2001.932281x

Hsiao, T. C., Pasquale, A. E., Ae, S., Fereres, E., & Steduto, P. (2007). A systematic and quantitative approach to improve water use efficiency in agriculture. https://doi.org/10.1007/s00271-007-0063-2.*25*3209231.

Jury, W. A., & Horton, R. (2004). Water characteristic function. *Soil Physics*, *384*. https://books.google.com/books/about/Soil_Physics.html?id=E5HZDwAAQBAJ

Kaptein, N. D., Light, M. E., & Savage, M. J. (2019). Sensors for the improvement of irrigation efficiency in nurseries. *Water SA*, *45*(3), 527–535. https://doi.org/10.17159/wsa/2019.v45.i3.6750

Keller, J., & Bliesner, R. D. (n.d.). *Sprinkler and trickle irrigation*. Retrieved October 26, 2025, from. https://rexresearch1.com/IrrigationLibrary/SprinkleTrickleIrrigation.pdf

Kramer, J., & Boyer, S. (1995). *Water Relations of Plants and Soils - Paul J. Kramer, John S. Boyer - Google Books*. https://books.google.lk/books?hl=en&lr=&id=H6aHAwAAQBAJ&oi=fnd&pg=PP1&dq=Kramer,+P.+J.,+%26+Boyer,+J.+S.+(1995).+Water+relations+of+plants+and+soils.+Academic+-Press.&ots=BZKb4YQ89N&sig=cU2ypWLwlaZwZgVy4keaksSl-_Q&redir_esc=y#v=onepage&q=Kramer%2C P. J.%2C.

Kumar, D., Singh, M., Kushwaha, M., Makarana, G., & Yadav, M. R. (2021). Integrated use of organic and inorganic nutrient sources influences the nutrient content, uptake and nutrient use efficiencies of fodder oats (Avena sativa). *Indian Journal of Agronomy*, *66*(4), 466–473.

Li, M., Zhang, K., M Eldoma, I., Fang, Y., & Zhang, F. (2020). Plastic Film Mulching Sustains High Maize (Zea mays L.) Grain Yield and Maintains Soil Water Balance in Semiarid Environment. *Agronomy*, *10*(4), 600. https://doi.org/10.3390/agronomy10040600

Liu, Z., Li, P., Hu, Y., & Wang, J. (2015). Wetting patterns and water distributions in cultivation media under drip irrigation. *Computers and Electronics in Agriculture*, *112*, 200–208. https://doi.org/10.1016/j.compag.2015.01.003

Manikandan, M., & Ravikumar, V. (2020). Soil Matric Potential Based Irrigation Schedule for Brinjal. *International Journal of Current Microbiology and Applied Sciences*, *9*(8), 3602–3612. https://doi.org/10.20546/ijcmas.2020.908.415

Murray, C. J. L., Callender, C. S. K. H., Kulikoff, X. R., Srinivasan, V., Abate, D., Abate, K. H., Abay, S. M., Abbasi, N., Abbastabar, H., Abdela, J., Abdelalim, A., Abdel-Rahman, O., Abdi, A., Abdoli, N., Abdollahpour, I., Abdulkader, R. S., Abebe, H. T., Abebe, M., Abebe, Z., … Lopez, A. D. (2018). Population and fertility by age and sex for 195 countries and territories, 1950–2017: a systematic analysis for the Global Burden of Disease Study 2017. *The Lancet*, *392*(10159), 1995–2051. https://doi.org/10.1016/S0140-6736(18)32278-5

Çolak, Y. B., Yazar, A., Sesveren, S., & Çolak, İ. (2017). Evaluation of yield and leaf water potential (LWP) for eggplant under varying irrigation regimes using surface and subsurface drip systems. *Scientia Horticulturae*, *219*, 10–21. https://doi.org/10.1016/J.SCIENTA.2017.02.051

Phogat, V., Skewes, M. A., Cox, J. W., Alam, J., Grigson, G., & Šimůnek, J. (2013). Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. *Agricultural Water Management*, *127*, 74–84. https://doi.org/10.1016/j.agwat.2013.05.017

Raja, M., Sundaram, S., & Ramasamy, S. (2019). (PDF) Growth and Yield Response to Brinjal (Solanum melongena L.) Varieties to the Application of Bio-stimulants. https://www.researchgate.net/publication/396198497_Growth_and_Yield_Response_to_Brinjal_Solanum_melongena_L_Varieties_to_the_Application_of_Bio-stimulants

Robertson, J., Thomas, C. J., Caddy, B., & Lewis, A. J. M. (1984). Particle size analysis of soils — A comparison of dry and wet sieving techniques. *Forensic Science International*, *24*(3), 209–217. https://doi.org/10.1016/0379-0738(84)90186-5

Saxton, K. E., & Rawls, W. J. (2006). Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science Society of America Journal*, *70*(5), 1569–1578. https://doi.org/10.2136/sssaj2005.0117

Schaap, M. G., Leij, F. J., & Van Genuchten, M. T. (2001). rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology*, *251*(3–4), 163–176. https://doi.org/10.1016/S0022-1694(01)00466-8

Sharma, N., Hakkim, A. V. M., & Singh, A. K. (2021). Development and field evaluation of a low-cost automated drip irrigation system. *Journal of Soil and Water Conservation*, *20*(2), 188–194. https://doi.org/10.5958/2455-7145.2021.00023.0

Shivani, S., Bhutia, T. L., Kumar, S., & Singh, A. K. (2019). Influence of drip irrigation and polyethylene mulch on growth, yield and water productivity of tomato (Solanum lycopersicum) and brinjal (Solanum melongena) cultivars in eastern plains. *Indian Journal of Agricultural Sciences*, *89*(4), 734–740. https://doi.org/10.56093/IJAS.V89I4.88875

Singandhupe, R. ., Antony, E., James, B. ., & Kumar, A. (2016). *EfficientwateruseforbrinjalSolanummelongenacropproduction throughdripirrigation.pdf*.

Singandhupe, R. B., Antony, E., James, B. K., & Kumar, A. (2007). Efficient water use for brinjal (Solanum melongena) crop production through drip irrigation. *Indian Journal of Agricultural Sciences*, *77*(9), 591–595. https://www.researchgate.net/publication/293342252_Efficient_water_use_for_brinjal_Solanum_melongena_crop_production_through_drip_irrigation

Song, W., Han, F., Bao, Z., Chai, Y., Wang, L., Huang, C., Cheng, H., & Chang, L. (2024). Mulching Practices Improve Soil Moisture and Enzyme Activity in Drylands, Increasing Potato Yield. *Agronomy*, *14*(5), 1077. https://doi.org/10.3390/agronomy14051077

Vallejo-Gómez, D., Osorio, M., & Hincapié, C. A. (2023). Smart Irrigation Systems in Agriculture: A Systematic Review. *Agronomy*, *13*(2), 1–25. https://doi.org/10.3390/agronomy13020342

Van Bavel, J. (2013). The world population explosion: causes, backgrounds and projections for the future. *Facts, Views & Vision in ObGyn*, *5*(4), 281–291. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3987379/

Weil, R., & Brady, N. (2017). *The Nature and Properties of Soils* (15th edition).

Yang, P., Wu, L., Cheng, M., Fan, J., Li, S., Wang, H., & Qian, L. (2023a). Review on Drip Irrigation: Impact on Crop Yield, Quality, and Water Productivity in China. *Water (Switzerland)*, *15*(9), 1733. https://doi.org/10.3390/w15091733

Yang, P., Wu, L., Cheng, M., Fan, J., Li, S., Wang, H., & Qian, L. (2023b). Review on Drip Irrigation: Impact on Crop Yield, Quality, and Water Productivity in China. *Water*, *15*(9), 1733. https://doi.org/10.3390/w15091733

Zhang, Y. Y., Zhao, X. N., & Wu, P.Te. (2015). Soil wetting patterns and water distribution as affected by irrigation for uncropped ridges and furrows. *Pedosphere*, *25*(3), 468–477. https://doi.org/10.1016/S1002-0160(15)30014-X