International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

Performance of A Soil Moisture-Based Drip Irrigation System Under Contrasting Rainfall Conditions in Tomato Cultivation

Quevedo-Nolasco Abel
Department of Hydrosciences
Colegio de Postgraduados
Montecillo, Mexico

Aguado-Rodríguez Graciano-Javier
Department of Hydrosciences
COLPOS-SECIHTI
Montecillo, Mexico

Abstract* - Efficient irrigation management is essential to reduce water use in agriculture, particularly under conditions of variable rainfall. The proliferation of open-source hardware and low-cost sensors has enabled the development of automatic irrigation systems based on soil moisture sensing; however, their performance under real rainfall conditions remains insufficiently documented. The objective of this study was to develop and evaluate a soil-moisture-based automatic irrigation system with a Human–Machine Interface (HMI), capable of maintaining a minimum soil moisture threshold while integrating rainfall under field conditions. The system was built using an Arduino microcontroller, soil moisture sensors, a tipping-bucket rain gauge, and a drip irrigation system, and was tested on potted tomato plants (Solanum lycopersicum var. cerasiforme) at two nearby sites with contrasting rainfall conditions. Results showed that the system successfully maintained soil moisture within user-defined thresholds while minimizing irrigation events. Total irrigation water applied during the crop cycle was 12.09 L per plant at Site 1 and 13.67 L per plant at Site 2, indicating that rainfall supplied a substantial portion of crop water requirements. Irrigation frequency was significantly higher during periods of low rainfall (1.93–2.16 irrigations day^{-1}) than during the rainy period (0.51–0.59 irrigations day^{-1}), demonstrating the adaptive response of the system to environmental conditions. These results indicate that soil-moisture-based irrigation systems integrating rainfall can significantly reduce irrigation water use while maintaining adequate soil moisture levels, highlighting their potential for improving water-use efficiency in agricultural production under variable climatic conditions.

Keywords - Arduino; FDR sensor; drip irrigation; rainfall monitoring; 3D printing

I. INTRODUCTION

As agriculture is the primary source of food in many countries, effective irrigation systems are crucial [1]. In recent years, several studies have implemented irrigation control systems using Arduino microcontrollers and soil moisture sensors [2]-[4]. In addition, some authors have employed drip irrigation as the irrigation method in Arduino-based prototypes due to its performance and efficiency [5].

Based on the above, and considering the importance of conducting studies aimed at improving water-use efficiency and food production, the objective of this study was to develop and evaluate a soil-moisture-based automatic irrigation system with a HMI, capable of maintaining a minimum soil moisture threshold and integrating rainfall under real field conditions, in order to quantify irrigation frequency and total water applied during different rainfall periods. This approach is aligned with the global trend of promoting technology transfer within the framework of Climate-Smart Agriculture (CSA) to support farming communities.

II. MATERIALS AND METHODS

The automatic irrigation device was designed and developed at the facilities of the Colegio de Postgraduados, Campus Montecillo. The project was carried out and evaluated in two main stages: (A) development of the device and (B) testing of the device.

A. Device development

The irrigation system was based on a control strategy in which soil moisture in the pot was monitored in real time at an hourly scale. After each soil moisture reading, if the measured value dropped below a user-defined threshold, the system activated irrigation for a duration also defined by the user. To implement this strategy, the development process consisted of several steps. First, the required materials for the device were selected. Second, these components were connected to an Arduino microcontroller, which coordinated the operation of the system. Third, a program was developed to enable the microcontroller to identify each component, acquire sensor data, and execute irrigation control decisions. Finally, all components were considered in the design of a protective enclosure, ensuring that the elements remained fixed and protected from movement or damage. Once assembled, the complete system was subjected to functional testing to verify the proper operation of the electronic components.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

Materials for the device. To develop the automatic irrigation device, a BGT-SM1(Z2)™ sensor was used to measure soil temperature and soil moisture. Soil moisture measurement was based on the frequency domain reflectometry (FDR) method. The sensor allows soil moisture measurement either through an analog output or via the RS-485 communication protocol [6]. According to the manufacturer, the sensor operates within a temperature range of −40 to 80 °C and measures soil moisture in a range of 0–50 %, using a calibration equation provided by the manufacturer. This sensor was selected because it has shown adequate performance in previous studies.

For system control and data management, the following components were used: two Steren™ power supplies (model ELI-1200) to power the Arduino™ board and the relay module; an Arduino™ Mega 2560 microcontroller; a DS1302 real-time clock module; a 3.5-inch Thincol™ touch screen for user–device interaction; a microSD module (model MLMSD) with a microSD memory card for storing precipitation data and irrigation events with date and time; and an 8-channel 5 VDC relay module used to control the motorized valve and activate the BGT-SM1(Z2) ™ sensor.

Additional components included two 3.5-mm female ports mounted on the enclosure to receive soil moisture and soil temperature signals, two 3.5-mm male connectors to transmit sensor outputs to the device, four 2.5-mm male connectors to supply power to the motorized globe valve and the Arduino board, and an RJ11 female port to receive precipitation data from the rain gauge. Precipitation was measured using a tipping-bucket rain gauge (WH-SP-R MISOL™) with a rainfall collection area of 150 × 60 mm.

The enclosure for the device was fabricated using 3D printing, employing approximately 0.5 kg of PLA filament (1.75 mm diameter). Irrigation control was achieved using a ¾-inch motorized globe valve. The total cost of the control system and electronic components was approximately USD 356, excluding irrigation pipes and water storage components.

Circuit connections. To establish communication among system components, all modules were connected by wiring to the Arduino™ Mega 2560 microcontroller, as shown in Figure 1. It should be noted that ground (GND) and 5 V (VCC) connections are not shown in Figure 1. This omission was made because the MLMSD and DS1302 modules were permanently powered, while the rain gauge was permanently connected to ground through a digital port, with the precipitation signal received through a separate digital input.

The relay module was permanently connected to 5 V, and relay activation was achieved by switching the ground (GND) signal. Regarding the BGT-SM1(Z2) sensor, the sensor was permanently connected to ground and disconnected from the 5 V supply through a relay (R SM1) until a soil moisture or temperature reading was required, at which point the sensor was powered.

The motorized globe valve received power through relay control, using one relay for valve opening (R VA) and a second relay for valve closing (R VC). The touch screen is not shown in Figure 1 because it was used as a shield mounted directly on the Arduino board; electrical connection was established automatically by aligning the pins during installation.

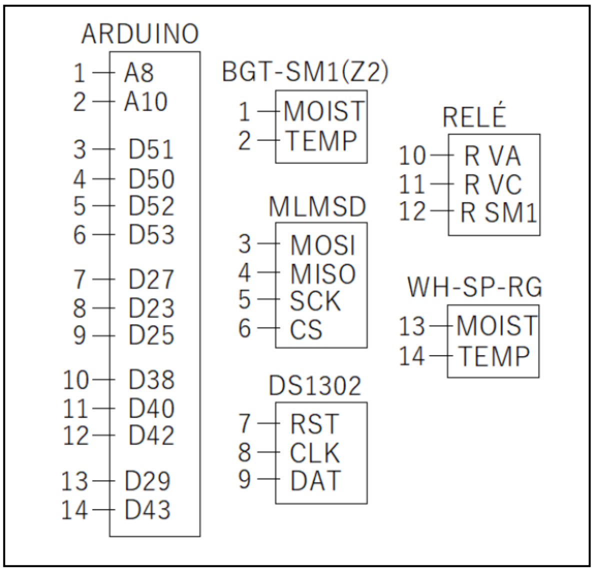

Fig. 1. Connection of the digital (D) and analog (A) pins of the Arduino board to the corresponding pins of the real-time clock module (DS1302), memory module (MLMSD), tipping-bucket rain gauge (WH-SP-RG), and relay module (RELÉ), which controls motorized valve opening (R VA), valve closing (R VC), and activation of the soil moisture sensor (R SM1), while the BGT-SM1(Z2) soil sensor provides analog outputs for soil temperature (TEMP) and soil moisture (MOIST); ground (GND) and 5 V (VCC) connections are not shown.

Program development. To establish communication between the microcontroller and the system modules, several software libraries were used. For the MLMSD memory module, the SdFat.h library was implemented [7]. For the DS1302 real-time clock module, the DS1302.h library was used [8]. The 3.5-inch Thincol touch screen required multiple libraries, including Adafruit_GFX.h [9], MCUFRIEND_kbv.h [10], and TouchScreen.h [11]. For the touch screen, minimum and maximum pressure thresholds were defined in the code (200 and 1000, respectively).

The program was designed to periodically check soil moisture and determine whether irrigation was required, operating primarily within this control loop, which consisted of approximately 304 lines of code. In parallel with this loop, the program enabled user interaction through the Thincol touch screen, allowing modification of system parameters related to substrate properties and irrigation management; this user–device interaction required approximately 1,777 lines of code.

As shown in Figure 2 (left), substrate-related variables that could be modified included field capacity, permanent wilting point, pot volume, and substrate type. For irrigation management (Figure 2, right), the adjustable variables were irrigation interval, irrigation duration, and measurement interval.

Enclosure design and fabrication. The enclosure was designed using AutoCAD™, according to the dimensions required by the different electronic components, allowing them to be securely mounted using small screws. Prior to printing the complete enclosure, individual sections were printed separately to verify dimensional accuracy and ensure proper alignment of screw perforations and component fittings, thereby preventing gaps through which small organisms (e.g., insects or spiders) could enter.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

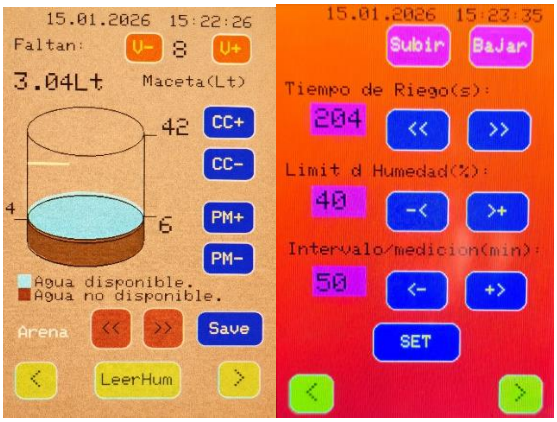

Fig. 2. Program interface displaying the adjustable variables related to substrate properties (left) and irrigation settings (right).

Once dimensional compatibility was confirmed, the components were positioned inside the enclosure, and the final parts were fabricated using an Ender™ 3 V2 3D printer. The printing times for each component were as follows: large rear cover (10 h 48 min), small rear cover (2 h 11 min), front frame (2 h 08 min), internal Arduino support (3 h 35 min), main housing (25 h 53 min), support for 2.5-mm female ports (18 min each, printed in quadruplicate), and support for 3.5-mm female ports (12 min each, printed in duplicate).

Fig. 3. Main 3D-printed components used for fabricating the enclosure of the automatic irrigation device.

Component testing. The different components of the developed device were assembled inside the fabricated enclosure, as shown in Figure 4.

It is worth noting that, because the soil moisture sensor operates with an analog signal, special care was taken to minimize electrical noise from the measurement point to the control device, which was located approximately 5 m away.

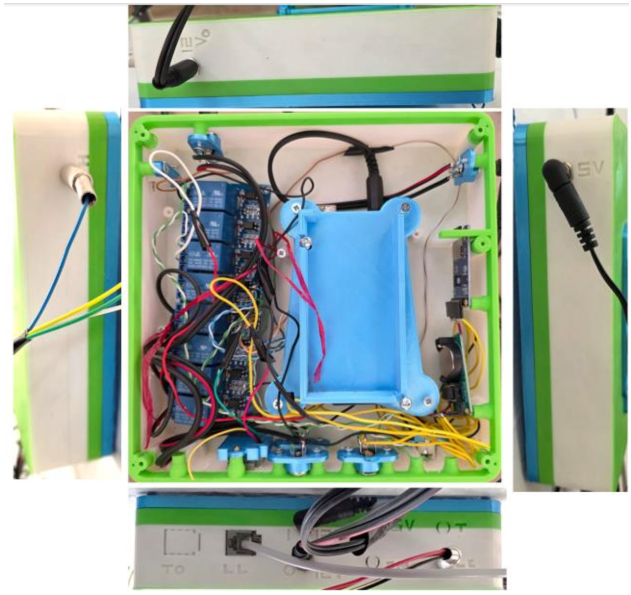

Fig. 4. Internal view of the automatic irrigation device showing the electronic components assembled inside the fabricated enclosure.

To reduce signal interference, the sensor signal cable was shielded with aluminum foil and wrapped with bare copper wire, which was connected to the Arduino ground (GND). Subsequently, the entire cable was placed inside a 16-mm irrigation hose to protect it from solar radiation. Finally, insulating tape was applied to prevent water ingress and the entry of small animals into the hose, as shown in Figure 5.

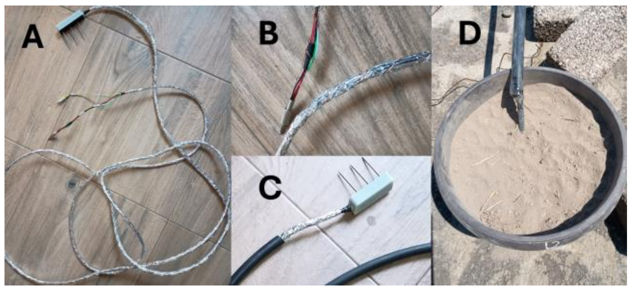

Fig. 5. Stepwise protection of the soil moisture sensor signal cable, including aluminum foil shielding (A), grounding using bare copper wire (B), placement inside a 16-mm irrigation hose for protection against solar radiation (C), and final sealing with insulating tape before installation in the pot (D).

B. *Device testing*

The irrigation system was implemented in duplicate in order to evaluate its performance at two different sites. The first test was conducted at the facilities of the Colegio de Postgraduados, Campus Montecillo (Site 1), located at 19°27′37.0″ N, 98°54′12.2″ W. The second test was installed at a nearby location (Site 2), located at 19°30′00.1″ N, 98°53′04.7″ W.

System establishment at Site 1. The irrigation system was initially installed using a single plantless pot (volume: 0.1845 ft^3 or 5.225 dm^3) during the testing period from April 8 to April 23 (Figure 6, top). Subsequently, the system operated with a

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

total of three additional pots during the period from April 24 to May 20. Cherry tomato plants (Solanum lycopersicum var. cerasiforme) were transplanted on May 21.

Fig. 6. Installation and initial performance testing of the device at Site 1 (top) and Site 2 (bottom).

Loam soil collected from a field at the Colegio de Postgraduados (same site) was used as the substrate. A rain gauge was not available at the beginning of the experiment and was therefore installed on May 23, carefully leveled to ensure accurate measurements.

Regarding soil moisture control, different minimum moisture thresholds were established throughout the experiment: 22% during days 0–3 (April 8–11), 19% during days 4–92 (April 12–July 9), 25% during days 93–106 (July 10–23), and 28% during days 107–137 (July 24–August 23). No soil fertilization was applied. The soil moisture sensor was installed at a depth of 5–10 cm, with the sensor probes spanning this depth range.

System establishment at Site 2. At Site 2, the irrigation system was initially installed using sand as the substrate during the testing phase (Figure 6, bottom), with a single plantless pot from April 8 to April 24. During this period, manual irrigation was applied to saturate the pot, allowing the sensor to detect moisture depletion over time. The pot volume was 0.1845 ft^3 (5.225 dm^3).

Subsequently, the system was operated with a total of five pots containing the same substrate during the period from April 25 to June 5. However, plant growth was not observed despite rainfall and measurable soil moisture. Consequently, when tomato plants were transplanted on June 6, the substrate was replaced with loam soil collected from a field at the Colegio de Postgraduados (19°27′37.0″ N, 98°54′12.2″ W).

The rain gauge was installed and carefully leveled on April 7; therefore, day zero of the experiment was defined as April 8, 2025. Soil moisture thresholds were adjusted during the experiment as follows: 15% during days 0–20 (April 8–28), 20% during days 21–70 (April 29–June 17), 22% during days 71–97 (June 18–July 14), 25% during days 98–114 (July 15–31), and 28% during days 115–160 (August 1–September 15). No fertilization was applied, and the soil moisture sensor was installed at a depth of 5–10 cm.

Control treatment at Site 2. A control pot was monitored using a BGT-SEC (Z2) soil moisture sensor installed in a separate pot without the main irrigation sensor. This sensor provides a digital output and does not saturate under high soil moisture conditions. It should be noted that the cost of the BGT-SEC (Z2) sensor is slightly more than twice that of the BGT-SM1 (Z2) sensor.

The BGT-SM1 (Z2) sensor continuously measured soil moisture in the main experimental pot throughout the experiment at Site 2 and was installed at a depth of 5 cm. During the initial phase, the control pot did not receive automated irrigation and was only manually irrigated to reach saturation. This approach allowed verification of faster soil moisture depletion in the absence of the irrigation system. On day 42 of the experiment, the control pot was connected to the irrigation system and began receiving automated irrigation.

Drip irrigation system configuration and emitter calibration. It is important to note that, at both sites, 8 L h^{-1} pressure-compensating drip emitters (Wade Rain™, model PC8) were installed. Each emitter was equipped with two stakes. According to the manufacturer, a minimum operating pressure of 0.5 bar is required for the emitter to begin discharging water, delivering approximately 7.6 L h^{-1} under these conditions.

As shown in Figure 6, the water supply source at both sites was located at a relatively low elevation, with a maximum water head of 1.1 m. This pressure (equivalent to 1.1 m of water column) was insufficient to activate the pressure-compensating mechanism of the emitters, which requires approximately 5.1 m of water column. Due to this limitation, all emitters were disassembled and the internal rubber diaphragm responsible for pressure compensation was removed, allowing water to flow under low-pressure conditions.

Following this modification, the emitter discharge rate was recalibrated. At Site 1, water from four emitters (eight stakes) was simultaneously collected in a container over a measured time interval. The mass of collected water was 3362 g, obtained by subtracting the container mass without water (319 g) from the mass with collected water (3681 g). The collection time was 34 min and 7 s (2047 s). Assuming a water density of 1 g mL^{-1}, the combined discharge rate of the four emitters was 1.6424 mL s^{-1} (3362 g / 2047 s).

Because each emitter supplied a single pot, the discharge rate per emitter was 0.4106 mL s^{-1} (1.6424 mL s^{-1} / 4 emitters), corresponding to 1478.16 mL h^{-1}. Therefore, the calibrated emitter flow rate was 1.47816 L h^{-1}. Given that the distance between emitters was minimal (<2 m), pressure differences due to head losses in the 16-mm irrigation tubing were considered

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

negligible, and uniform discharge among emitters was assumed.

Initial irrigation after transplanting. At both sites, immediately after transplanting the tomato plants, the soil was irrigated to saturation moisture conditions.

Data processing. The device stored data in separate text files for precipitation and irrigation events. Precipitation data were recorded each time a tipping event was detected by the tipping-bucket rain gauge sensor. Each tip represented 0.2794 mm of precipitation [12]. Previous studies have reported a very similar tipping value (0.28 mm), indicating that recalibration of the manufacturer's specification was not required, provided that the rain gauge was properly leveled.

Consequently, precipitation data were available with precise date and time stamps corresponding to each recorded 0.2794-mm event. Daily precipitation totals (mm) were obtained by summing the individual tipping events using Microsoft Excel.

With respect to irrigation data, each irrigation event was logged with detailed information, including irrigation start and end times, irrigation duration (s), date and time, soil moisture (%), and soil temperature (°C). The dataset was filtered to retain only irrigation start events, and each irrigation initiation was plotted as an individual data point.

III. RESULTS

Tomato plants grew throughout the period during which the irrigation system was in operation. Photographs were taken on different dates to document plant growth. The dates on which the photographs were taken and the corresponding images are shown in Figure 7.

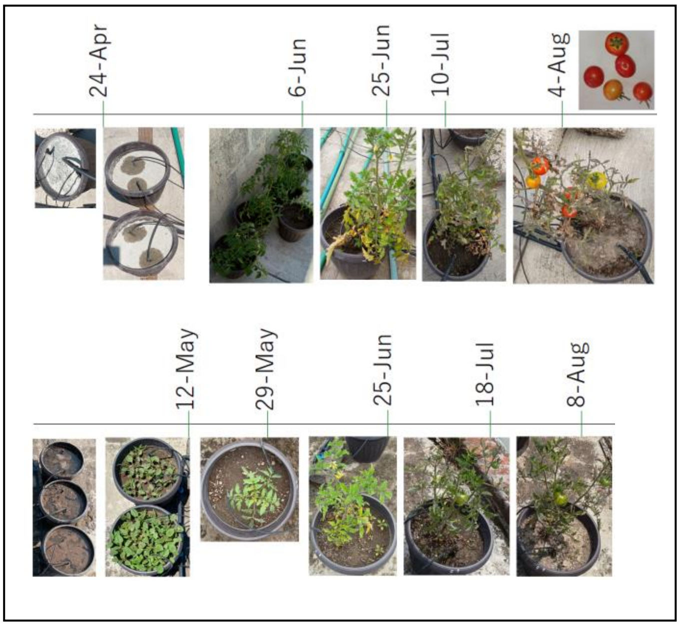

Fig. 7. Sequential photographs illustrating plant growth during the experimental period at Site 2 (top) and Site 1 (bottom).

With respect to the recorded data, a graphical representation was obtained for Site 1, as shown in Figure 8.

According to the precipitation patterns shown in Figures 8 and 9, low-rainfall events occurred during the initial phase of the experiment, corresponding to days 0 to 43. In contrast, a period with higher precipitation was observed from day 44 onward, extending to day 136 at Site 1 and to day 160 at Site 2.

It should be noted that, at Site 1, a total of 459.05 mm of precipitation was recorded from day 45 to day 160 of the experiment. This was due to the absence of a rain gauge during the initial phase of the experiment. Therefore, precipitation data for days 0 to 44 were obtained from the rain gauge installed at Site 2.

Considering this, precipitation during the early phase of the experiment was relatively scarce, and some low-intensity rainfall events may not have been detected by the sensor. In this context, effective precipitation criteria were adopted following the general framework proposed by Allen *et al.* [13], and the specific approach described by Palacios Vélez [14], whereby daily precipitation below 1 mm is considered non-effective, as it does not contribute significantly to soil water storage.

Based on this criterion, the period from day 0 to day 43, which accumulated 41.35 mm of rainfall, was classified as a low-rainfall period, with an average daily precipitation of less than 1 mm day^{-1}. In contrast, the period from day 44 to day 136, which accumulated 386.69 mm of rainfall, was classified as a rainfall period, with an average daily precipitation greater than 1 mm day^{-1}.

Regarding irrigation events, a total of 83 irrigations were applied during the low-rainfall period (days 0–43), whereas 47 irrigations were applied during the rainfall period (days 44–136). Additionally, each irrigation event had a fixed duration of 225 s, as programmed in the device.

Therefore, a total of 18,675 s of irrigation (83 irrigations × 225 s) were applied during the low-rainfall period, and 10,575 s of irrigation (47 irrigations × 225 s) during the rainfall period.

These irrigation times correspond to 5.1875 h (18,675 s / 3600 s) during the low-rainfall period and 2.9375 h (10,575 s / 3600 s) during the rainfall period. Based on the calibrated emitter discharge rate of 1.48816 L h^{-1}, a total of 7.71983 L of water was applied during the low-rainfall period (days 0–43), whereas 4.37147 L was applied during the rainfall period (days 44–136).

Overall, 12.0913 L of water per pot were applied over the crop cycle at Site 1, considering plants transplanted at approximately one month of age.

In contrast, data from Site 2 were plotted as shown in Figure 9.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

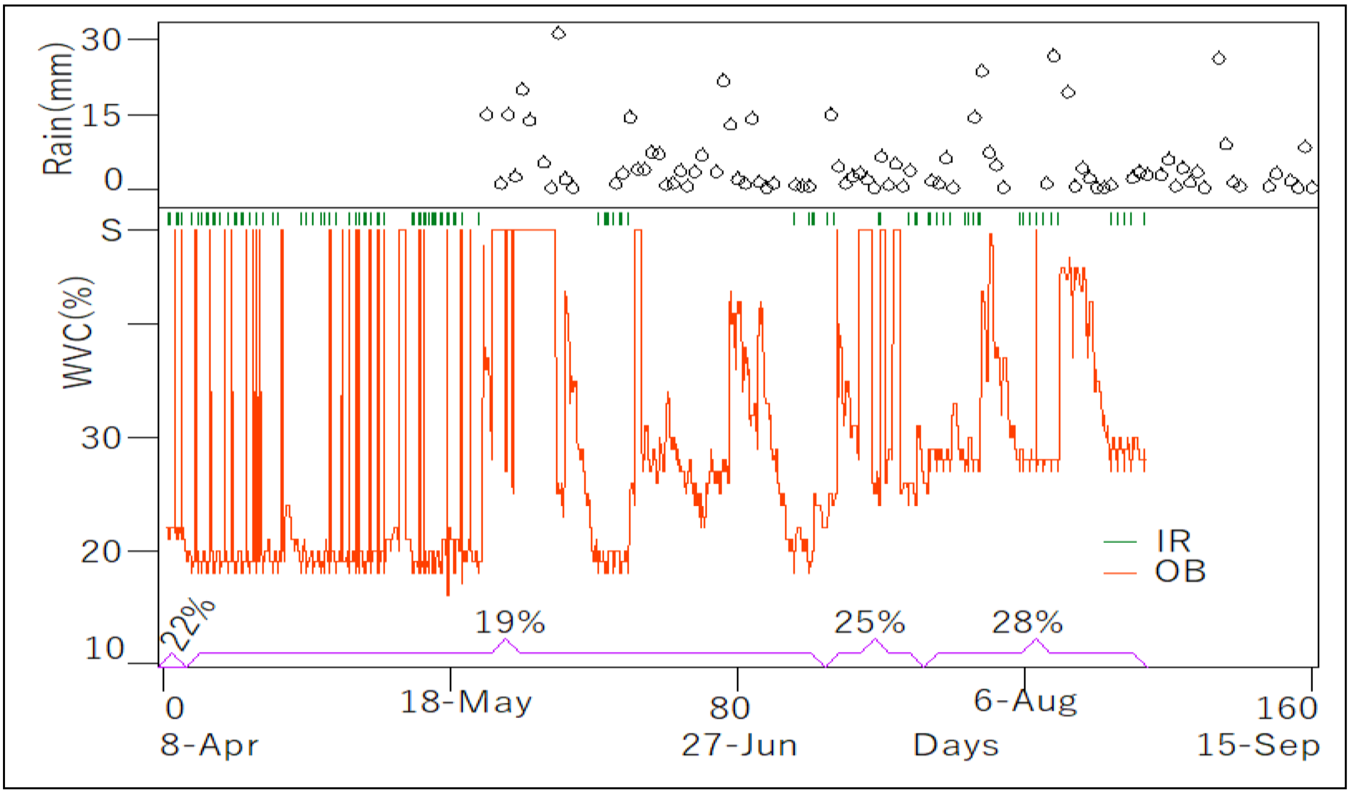

Fig. 8. Time series of soil volumetric water content (VWC, %) observed in the pot containing the BGT-SM1(Z2) sensor (OB), irrigation events (IR), and daily precipitation (Rain, mm) recorded by the WH-SP-RG™ rain gauge over the experimental period (Days) at Site 1, with the purple lines indicating the user-defined minimum soil moisture thresholds applied during different stages of the experiment.

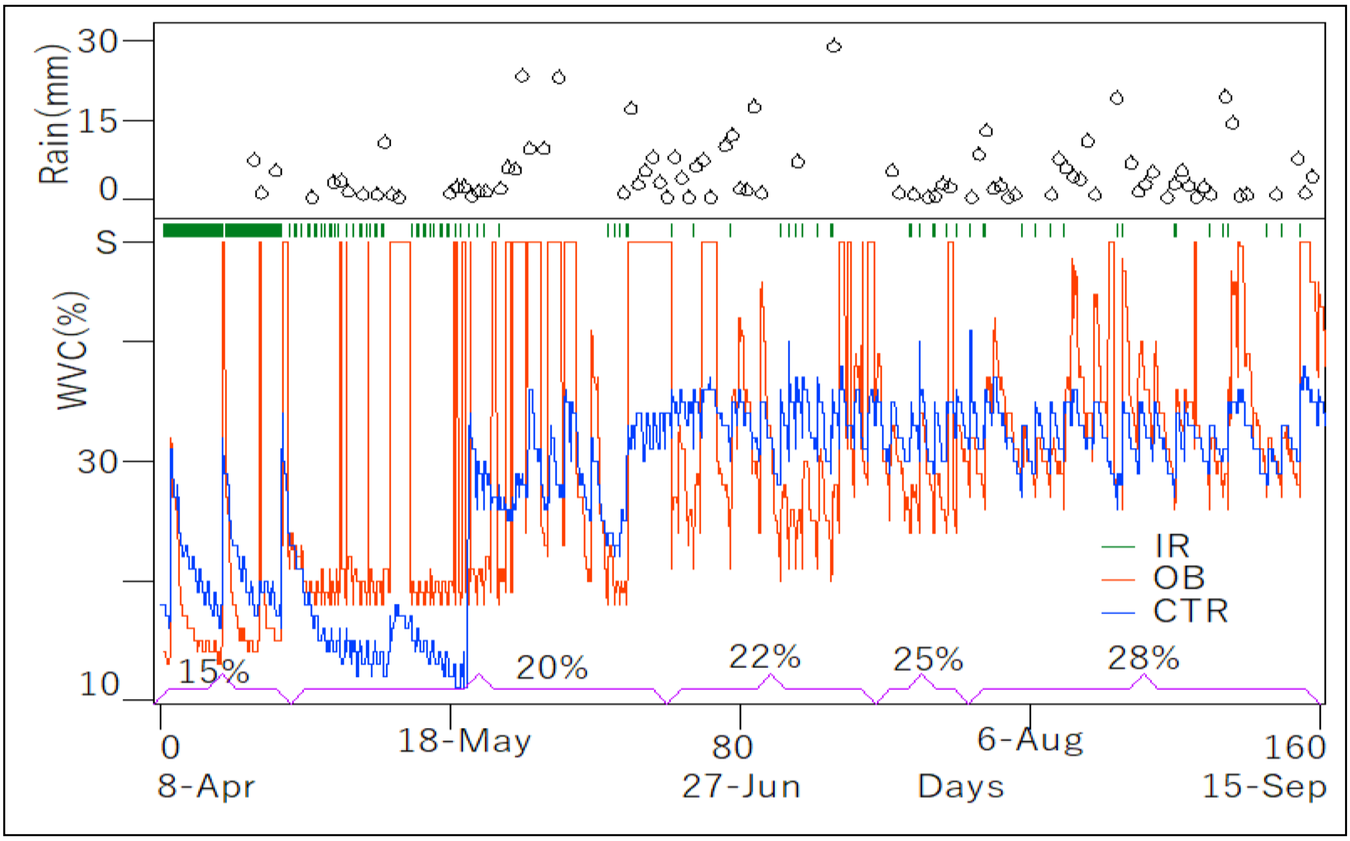

Fig. 9. Time series of soil volumetric water content (VWC, %) observed in the pot containing the BGT-SM1(Z2) sensor (OB), control treatment measured with the BGT-SEC(Z2) sensor (CTR), irrigation events (IR), and daily precipitation (Rain, mm) recorded by the WH-SP-RG™ rain gauge over the experimental period (Days) at Site 2, with the purple lines indicating the user-defined minimum soil moisture thresholds applied during different stages of the experiment.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 02 , February - 2026

At Site 2, a total of 437.54 mm of precipitation was recorded from day 0 to day 160 of the experiment. However, for the purpose of estimating irrigation water use, the plant was removed after harvest on day 136. Therefore, the same analysis periods defined for Site 1 were applied. During the low-rainfall period (days 0–43), a total of 41.35 mm of precipitation was recorded, whereas 328.29 mm were recorded during the rainfall period (days 44–136).

With respect to irrigation at Site 2, irrigation events with a duration of 24 s were applied from day 0 to day 16, whereas irrigation events with a duration of 225 s were applied from day 16 to day 43. Therefore, irrigation times recorded from day 0 to day 16 were summed, resulting in a total of 10,465 s, which is equivalent to 47 irrigation events of 225 s (rounded up to the nearest integer to avoid underestimation of water consumption).

From day 16 to day 43, a total of 46 irrigation events were recorded. On day 16, the irrigation duration was adjusted; consequently, irrigation events with both durations were recorded on that day. Thus, during the low-rainfall period (days 0–43), a total of 93 irrigation events equivalent to 225 s were considered.

In contrast, during the rainfall period (days 44–136), a total of 54 irrigation events were applied. Accordingly, total irrigation time amounted to 20,925 s (93 events × 225 s) during the low-rainfall period and 12,150 s (54 events × 225 s) during the rainfall period. These values correspond to 5.8125 h and 3.375 h of irrigation, respectively.

Based on the calibrated emitter discharge rate of 1.48816 L h^{-1}, a total of 8.64993 L of water was applied during the low-rainfall period (days 0–43), whereas 5.02254 L was applied during the rainfall period (days 44–136). Overall, 13.67247 L of water per pot were applied over the crop cycle at Site 2, considering plants transplanted at approximately one month of age.

IV. DISCUSSION

In this study, a total of 304 lines of code were required for the irrigation program to operate properly, performing soil moisture monitoring and irrigation control. However, implementing a user interface that allows users to easily adjust system parameters without requiring programming knowledge proved to be a more suitable approach, despite the increase in code length needed to support user–device interaction (1777 lines of code). Similar design choices have been reported in previous studies where user interaction is essential, such as the work by Guntur *et al*. [15], who also developed a system that offers a user-friendly interface enabling farmers to automatically control the irrigation process.

Several authors have reported that soil-moisture-based automatic irrigation systems can contribute to water savings by preventing excessive irrigation and reducing nutrient leaching caused by surface runoff [16], while maintaining irrigation according to real-time sensor readings [17]. These findings are consistent with the results of the present study, in which the irrigation system supplied only the water required by the crop (12.0913 L per plant at Site 1 and 13.67247 L per plant at Site 2), while maintaining the user-defined soil moisture thresholds throughout the experimental period (Figures 8 and 9).

The use of user-defined soil moisture thresholds has been explored in previous research. For instance, Zhu *et al.* [3], developed an Arduino-based automatic irrigation system that enabled regulation of soil water content within a specified range of 12–20%, reporting satisfactory system performance. In the present study, minimum soil moisture thresholds were defined within and beyond this range, reaching values of up to 28%, demonstrating the flexibility of the system to operate under different moisture conditions according to user requirements.

With respect to irrigation frequency, this study showed that, at Site 1, a greater number of irrigation events was required during the low-rainfall period, with 83 irrigations over 43 days, compared to the rainfall period, during which 47 irrigations were applied over 92 days. This corresponds to an average of 1.93 irrigations per day during the low-rainfall period and 0.51 irrigations per day during the rainfall period.

A similar pattern was observed at Site 2, where irrigation frequency averaged 2.16 irrigations per day during the low-rainfall period (93 irrigations over 43 days) and 0.59 irrigations per day during the rainfall period (54 irrigations over 92 days). These results are consistent with the findings of Gebremedhin *et al.* [18], who reported that the number of irrigation events depends on the duration of dry periods. Likewise, Sekyi-Annan *et al.* [19], found that greater irrigation requirements occur under conditions of low rainfall.

It should also be noted that the soil moisture sensor was installed at a depth of 5–10 cm. At this depth, the sensor is less directly affected by external factors such as surface evaporation or short-term atmospheric fluctuations. As a result, relatively low variability in soil moisture readings was observed over time. This behavior is consistent with the findings of Zhu *et al.* [3], who reported that the variation rate of volumetric water content (VWC) is slightly higher at shallower depths than at deeper depths. This effect was also observed during the experiment, as the soil surface occasionally exhibited lower moisture levels while the sensor readings indicated that the minimum moisture threshold had not yet been reached.

V. CONCLUSION

The soil-moisture-based irrigation system effectively maintained soil water content within predefined thresholds while integrating rainfall and drip irrigation. Total irrigation applied during the crop cycle was limited to 12.09–13.67 L per plant, indicating that rainfall supplied a substantial portion of crop water requirements and that unnecessary irrigation was avoided. Irrigation frequency increased during periods of low rainfall and decreased during the rainy period, demonstrating adaptive system behavior in response to environmental conditions. The user interface enhanced system usability, and sensor placement at 5–10 cm depth ensured stable soil moisture measurements suitable for irrigation control.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support provided by the Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECTIHTI) through project CIR/0027/2022: Strategies for collecting rainwater in semi-urban conditions for agricultural use. The authors also thank the Colegio de Postgraduados, Campus Montecillo, for providing the facilities required to conduct the experimental work.

REFERENCES

[1] C. K. Chan, P. D. Malwe, V. T. Mandlik, N. Jaiswal, S. B. Jadhav, N. Sapkal, N. Bhopale, C. R. Sonawane, S. Singh, D. Varshaney, and S. Kumar, "A solar-powered automated irrigation system using Arduino and moisture sensors for efficient water management in agriculture," Engineering, Technology & Applied Science Research, vol. 15, no. 4, pp. 24891–24896, 2025. doi: 10.48084/etasr.11206.

[2] Ç. Ersin, R. Gürbüz, and A. K. Yakut, "Application of an automatic plant irrigation system based on Arduino microcontroller using solar energy," Solid State Phenomena, vol. 251, pp. 237–241, 2016. doi: 10.4028/www.scientific.net/SSP.251.237.

[3] H. H. Zhu, Y. X. Huang, H. Huang, A. Garg, G. X. Mei, and H. H. Song, "Development and evaluation of Arduino-based automatic irrigation system for regulation of soil moisture," International Journal of Geosynthetics and Ground Engineering, vol. 8, no. 1, p. 13, 2022. doi: 10.1007/s40891-022-00360-8.

[4] Y. Jalajakshi, B. Anusha, G. Sanjay, C. Sandeep, and V. Shiva Nagaraju, "Modeling and designing of automatic plant watering system using Arduino," American Journal of Management and IoT Medical Computing, vol. 4, no. 4, pp. 279–283, 2025. doi: 10.64751/ajmimc.2025.v4.n4.pp279-283.

[5] T. A. Manfo and M. E. Şahinb, "Development of an automatic PV-battery powered water irrigation system with Arduino software for agricultural activities," Gazi Journal of Engineering Sciences (GJES), vol. 10, no. 2, 2024. doi: 10.30855/gmbd.0705A07.

[6] Beijing Guoxinhuayuan Technology, "Soil temperature and moisture sensor BGT-SM1(Z2) manual," Beijing, China, 2019. [Online]. Available: http://www.bjgxhy.com.

[7] B. Greiman, "SdFat: Arduino FAT16/FAT32/exFAT library, version 2.3.0," Arduino, 2024. [Online]. Available: https://docs.arduino.cc/libraries/sdfat/.

[8] R. Couto, "DS1302 Arduino library, version 1.1.0," Arduino, 2024. [Online]. Available: https://docs.arduino.cc/libraries/ds1302/.

[9] Adafruit Industries, "Adafruit GFX library, version 1.11.9," Arduino, 2024. [Online]. Available: https://docs.arduino.cc/libraries/adafruit-gfx-library/.

[10] D. Prentice, "MCUFRIEND_kbv library, version 3.0.0," Arduino, 2024. [Online]. Available: https://docs.arduino.cc/libraries/mcufriend-kbv/.

[11] Adafruit Industries, "TouchScreen library, version 1.1.4," Arduino, 2024. [Online]. Available: https://docs.arduino.cc/libraries/touchscreen/.

[12] Shenzhen Fine Offset Electronics, "Datasheet for wind vane, cup anemometer, and tipping-bucket rain gauge," 2025. [Online]. Available: https://www.hestore.eu/en/prod_getfile.php?id=13323. [Accessed: 7-Oct-2025].

[13] R. G. Allen, L. S. Pereira, D. Raes, and M. Smith, Crop evapotranspiration—Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No. 56, Rome, Italy, 1998.

[14] E. V. Palacios and A. Exebio, Introducción a la teoría de la operación de distritos de riego, 2nd ed., Centro de Hidrociencias, Colegio de Postgraduados, Mexico, 1989.

[15] J. Guntur, S. S. Raju, K. Jayadeepthi, and C. H. Sravani, "An automatic irrigation system using IoT devices," Materials Today: Proceedings, vol. 68, pp. 2233–2238, 2022. doi: 10.1016/j.matpr.2022.08.438.

[16] A. N. Samanta, M. Halder, T. Dhank, S. Roy, G. K. Das, and J. Datta, "Auto irrigation system using an Arduino Uno and soil moisture sensor," American Journal of Advanced Computing, vol. 2, no. 2, 2023. doi: 10.15864/ajac.22001.

[17] W. Warji, S. Suharyatun, A. Tusi, and A. B. Soma, "Development of a prototype automatic irrigation system using Arduino Uno for enhanced soil moisture management," International Journal of Design Nature and Ecodynamics, vol. 19, no. 5, pp. 1519–1526, 2024. doi: 10.18280/ijdne.190506.

[18] T. Gebremedhin, G. G. Haile, T. G. Gebremicael, H. Libsekal, and K. W. Reda, "Balancing crop water requirements through supplemental irrigation under rainfed agriculture in a semi-arid environment," Heliyon, vol. 9, no. 8, 2023. doi: 10.1016/j.heliyon.2023.e18727.

[19] E. Sekyi-Annán, B. Tischbein, B. Diekkrüger, and A. Khamzina, "Year-round irrigation schedule for a tomato–maize rotation system in reservoir-based irrigation schemes in Ghana," Water, vol. 10, no. 5, p. 624, 2018. doi: 10.3390/w10050624.