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Development of smart micro-irrigation system using Arduino Uno for okra cultivation in Bangladesh

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Abstract: Conventional irrigation practices result in a substantial amount of water loss with okra cultivation. Although micro-irrigation can address this issue by delivering water directly near the rootzone, it requires manual operation. These issues, however, can be resolved with the introduction of a smart micro-irrigation system. This study aims to develop a smart micro-irrigation system for okra, in conjunction with the sub-components of drip irrigation, a microcontroller, and a soil sensor. The experiment was laid out with a randomised complete block design (RCBD) having three treatments: (*i*) control irrigation (T_1), (*ii*) drip irrigation (T_2), and (*iii*) smart micro-irrigation (T_3). The experimental field was irrigated based on soil moisture regimes in the crop rootzone. The plant growth, yield, and water use efficiency were assessed to evaluate the system. The results showed no significant differences among these treatments (at $P < 0.05$). The best water usage efficiency (15.98 kg·m^{-3}) was observed in the T_3 treatment, which also provided about 13.10% water savings compared to the conventional irrigation. This study indicates that a smart micro-irrigation system could be a promising technology for water-efficient okra cultivation.

Keywords: drip irrigation; soil moisture sensor; solenoid valve; yield parameters; water use efficiency

Okra (*Abelmoschus esculentus*) is a crucial annual vegetable cultivated throughout the year in Bangladesh, with a particular preference for the summer season. The immature pods of okra are consumed as fresh or canned food and are also used for seed purposes (Dash et al. 2013). In Bangladesh, approximately 38% of the total vegetable production occurs during the Kharif season (June to October). The total production of okra in the growing season of 2020 to 2021 was 70 242 Mt from 12 189 ha of land, with an average yield of 5.7 t·ha^{-1} (Zannat et al. 2023). This is comparatively lower than the yields in other developed countries.

Efficient irrigation systems, improved cultural practices and high-yield varieties have the potential to increase the yield and size of the okra fruits, addressing the vegetable shortage in Bangladesh. Okra crops typically require about 547 mm of water during their whole growth, and, in the absence of adequate rainfall, approximately 38.1 mm of water eve-

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ry 10 days is recommended during their production period (Brandenberger et al. 2018). Due to surface irrigation practice in okra cultivation, substantial water losses occur due to evapotranspiration, seepage, percolation and dead storage. Additional water losses also occur through weeds (Haider et al. 2015). In order to mitigate these losses, micro-irrigation systems are being employed, saving water and increasing irrigation efficiency by delivering water at or near the rootzone (Lamm et al. 2012). Drip irrigation, a form of micro-irrigation, plays a crucial role in water conservation and enhances the crop productivity by efficiently utilising water (Saxena et al. 2013; Oliver et al. 2014; Kaarthikeyan and Suresh 2019). Non-automated drip systems, however, require manual operators for the operation, diagnosis and maintenance of the drippers and the laterals.

Moreover, unlike conventional irrigation systems, smart irrigation systems can foster the achievement of sustainable development goals in agriculture (Haider et al. 2015). These systems are precise, capable of estimating and measuring the current plant state, providing the desired amount of water, and reducing water losses and manual interventions during crop cultivation. Smart irrigation systems integrate intelligent technology with the irrigation system (Gutiérrez et al. 2013; Reche et al. 2015), with irrigation controllers regulating the watering based on soil moisture sensors. Sensor-based irrigation systems have been studied in various applications (Abdurrahman et al. 2015), where sensors send real-time values to a microcontroller, and the microcontroller communicates these values to a PC through serial communication (Broeders et al. 2013). Intelligent irrigation systems automatically optimise the watering plans and running hours to meet the specific needs of the landscape and deliver the right amount of water (Caetano et al. 2015; Houstis et al. 2017).

In recent days, several studies (Dobbs et al. 2014; Haghani et al. 2015; Reche et al. 2015; Jiang et al. 2018; Keswani et al. 2019) have focused on the development of smart irrigation systems for precise crop watering. Despite numerous efforts, the adoption of smart technologies by farmers has been rather slow. According to Islam et al. (2021), data connectivity and inadequate network functionalities are the most limiting factors. Moreover, the high cost of the technology, absence of soil and crop-specific data, ineffective pest control systems, and inefficient irrigation infrastructures are also responsible. It is, therefore, imperative that more agronomic information is generated for field crops under smart farming systems. The primary objective of this study is to contribute to this area of concern by developing the modalities of a smart micro-irrigation system capable of measuring soil moisture while delivering adequate amounts of irrigation water with precision to okra fields. This intelligent system aims to minimise over-irrigation, reduce labour requirements, and introduce a low-cost solution using Arduino microcontrollers coupled with soil moisture sensors.

MATERIAL AND METHODS

Main components of smart micro-irrigation system

Arduino Uno. The Arduino Uno is an open-source microcontroller board based on the ATmega328P microcontroller (Figure 1A). It features 14 digital input/output pins, with 6 of them capable of functioning as pulse width modification (PWM) outputs, while the remaining pins serve as analogue inputs (Senpinar 2019). The electronic devices and sensors can be easily connected to the corresponding plugs for each of these pins, making them ready for operation. This microcontroller is equipped with essential features, including a 16 MHz quartz crystal, a universal series bus (USB) connection, a power jack, and a reset button for proper functionality (Baraka et al. 2013). The Arduino is designed with all the

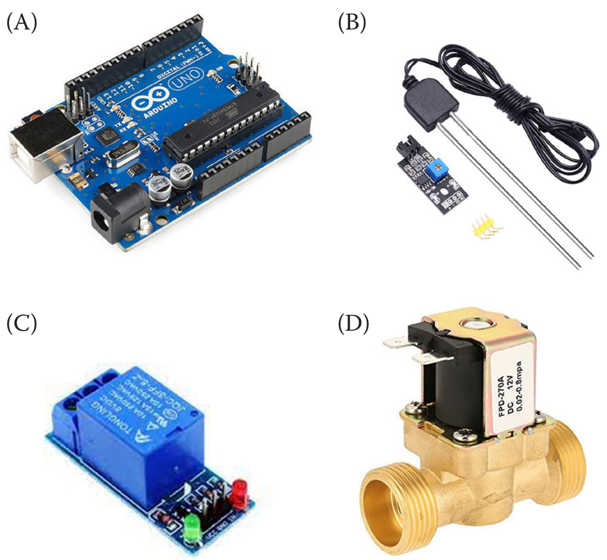

Figure 1. (A) Arduino microcontroller, (B) soil moisture sensor, (C) relay module, and (D) solenoid valve for a smart micro-irrigation system

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necessary components to support the microcontroller and can be effortlessly connected to a computer using a USB cable or powered with an adapter (6 V to 20 V).

Soil moisture sensor. A soil moisture sensor consists of two probes designed to measure the moisture content in the soil (Figure 1B). These probes enable the passage of an electric current through the soil, and the moisture content is determined based on the soil's resistance. The soil moisture sensor operates at a working voltage of 5 V, with a desired current of less than 20 mA. To connect the soil moisture sensor to the Arduino Uno, the voltage common collector (VCC) of the soil moisture sensor is linked to the 5 V pin on the Arduino Uno, the GND (ground) of the soil moisture sensor is connected to the GND of the Arduino board, and the signal wire (A0) of the sensor is connected to the A0 analogue pin on the Arduino (Baraka et al. 2013). The programmed code generates sensor values as outputs in the serial monitor.

Relay module. A 5 V relay module serves as an electrically operated switch for the main voltage, allowing the current to be turned off or on (Figure 1C). These relay modules come in various forms, including single-channel, double-channel, four-channel, and eight-channel variants (Souza e Silva Neto et al. 2017). A relay typically features three main connections for the main voltage: the common pin (COM), the normally open pin (NO), and the normally closed pin (NC). The COM and NO pins have no connection when the relay is turned off. When the relay is energised by the direct current (DC) power from the Arduino Uno, it connects to the COM pin, supplying power to the solenoid valve and opening it. The relay module input (IN) is also connected to the Arduino board.

Solenoid valve. A solenoid valve (Figure 1D) is an electro-mechanical operated valve that transforms alternating current (AC) or DC electrical energy into linear motion. Typically used to control the flow of a liquid in a pipe, the solenoid valve employed in the experiment is of the normally closed type and operates on 220 V AC power. In its default state, with no power supplied, the valve remains closed, preventing the passage of water. Upon receiving a power supply, the valve's plunger opens, allowing water to flow through.

Water pump. A 12 V water pump with a discharge capacity of 10 L·min^{-1} was employed solely for laboratory testing. The pump's delivery head was approximately 1.2 m to 1.5 m high, utilising a 0.0127 m diameter pipe. Remarkably, the power consumption of this pump was very low, approximately 0.5 A. In addition to the laboratory pump, a 1.12 kW single-phase pump was utilised in the research field to maintain the water in the water tank. This pump boasted a maximum flow rate of 55 L·min^{-1}, with a remarkable maximum head of up to 70 m (Zannat et al. 2023).

Drip irrigation system. Drip irrigation, as defined by the American Society of Agricultural and Biological Engineers (ASABE), involves the application of water below the soil surface using micro-irrigation drippers with a discharge rate usually less than 7.5 L·h^{-1}. The key component of drip irrigation is the dripper, also known as an emitter, which serves as the end device delivering water directly to the crop rootzone in tiny drops. This specific dripper was developed by the Department of Agricultural Engineering at Bangabandhu Sheikh Mujibur Rahman Agricultural University in Bangladesh (Oliver et al. 2016). It operates at an average flow rate of 3.5 L·h^{-1} and is designed as a pressure-compensated dripper. To convey water from the water source to the field, a main pipe with a diameter of 0.01905 m was utilised. A 0.0127 m lateral pipe, coupled with the main pipe, delivers water drop by drop directly to the crop rootzone through the drippers. Various connectors, including tee joints, end caps, clamps, and threaded pipes, were used to successfully set up the polyethylene drip pipe in the field. Additionally, a control valve was implemented to regulate the flow of water in the drip irrigation treatment section.

Calibration of the soil moisture sensor for programming

With the aid of programming, the smart micro-irrigation system utilises a moisture sensor to detect the soil's dryness value (limited to 1 023) displayed in the serial monitor of the Arduino IDE software. The soil moisture content is determined as an indicator of dryness. The higher the dryness value, the drier the soil gets. Random soil samples were collected from the experimental field at a depth of 0.1 m. The weight of these samples was measured in the laboratory, and the dryness of the soil was assessed using a soil moisture sensor. Subsequently, the samples were placed in a micro-oven at a temperature of 104 °C for 24 h. After removing the samples from the micro-oven, their weight was measured, and the dryness was determined by the soil mois-

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ture sensor, with the soil moisture recorded as zero. The oven-dry samples were then saturated by adding water, and the moisture content of these samples was measured, along with their dryness values. The process is further explained under soil moisture calibration subheading in the results and discussion. Arduino IDE, supporting C and C++ languages with specific code structuring rules (Souza et al. 2017), was used for programming. The IDE provides a software library for the wiring project, offering numerous input and output procedures (Reche et al. 2015).

Overall working procedure of smart micro-irrigation system

The detailed working procedure of the smart micro-irrigation system in the experimental field is outlined in the following steps (Figure 2):

Step 1. The soil moisture sensor is connected to the Arduino microcontroller, which is also linked to other electronic components, including a relay for the power supply and a relay for the solenoid valve. The soil moisture sensor is embedded in the soil, actively measuring the soil moisture. The sensor transmits this information and relevant parameters to the microcontroller, which, in turn, controls the solenoid valve (Figure 2).

Step 2. The system operates whenever the soil moisture level falls below a predetermined value. The microcontroller then sends a signal to the relay module to open the solenoid valve. A specific amount of water is delivered to the plant through the drippers integrated into the micro-irrigation system. Once the desired amount of water reaches the plant's rootzone, the watering process is automatically halted.

To execute the successful operation described above, the appropriate connection of various electronic components for the smart micro-irrigation system was established. Initially, a cable with three branches was connected to the soil moisture sensor using three jumper wires. Among these, one wire was connected to ground (GND), another to voltage common collector (VCC), and the remaining one to the A0 port of the soil moisture sensor. The corresponding ends of these jumper wires were connected to the Arduino board, with the VCC of the bridge cable linked to Arduino's 5 V, the GND connected to the Arduino GND, and the soil moisture sensor's A0 port connected to the Arduino's analogue port A0. The connection between the Arduino board and the relay module was also established. The GND port of the relay was connected to the ground, and the input (IN) port was linked to an Arduino digital pin to control the relay channel. When the relay received energy from Arduino Uno, power was supplied to the solenoid valve. The solenoid valve was connected to the NO (normally open) pin of the relay and a power adapter. Importantly, there was no connection between the COM (common) pin and NO (normally open) pin when the relay was switched off.

The soil moisture measurement was conducted using soil moisture probes embedded within the wetting zone of the okra plant. The sensor transmitted information and parameters related to the soil moisture to the microcontroller (Arduino Uno),

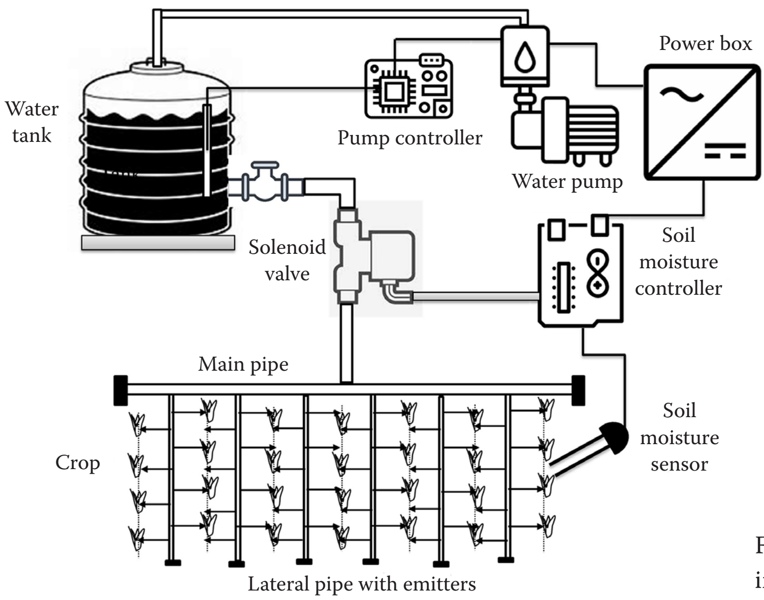

Figure 2. Schematic diagram of a smart micro-irrigation system using a soil moisture sensor

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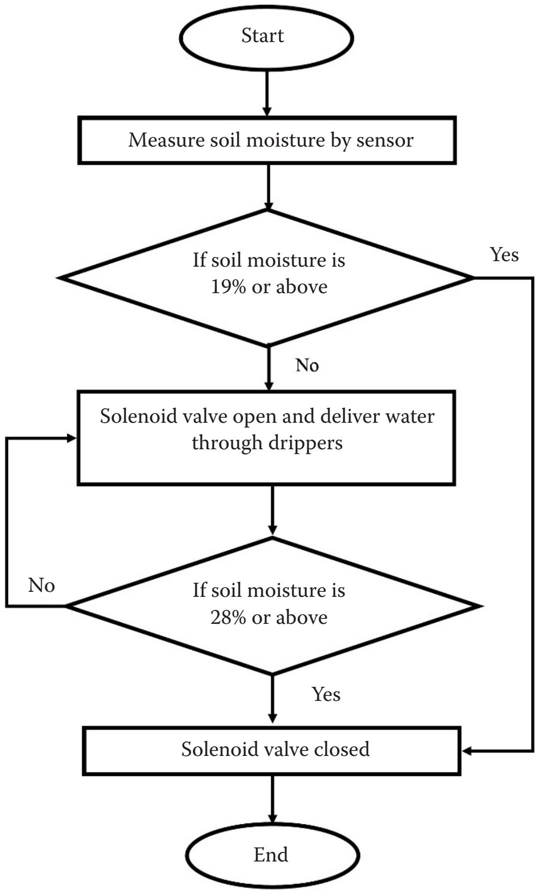


Figure 3. The algorithm of the smart micro-irrigation system

which, in turn, controlled the solenoid valve. If the soil moisture level was between 19% and 28%, the microcontroller would send a signal to the relay module to keep the solenoid valve closed. Only when the soil moisture level fell below 19%, the solenoid valve would open, delivering a specific amount of water to the rootzone of okra (Figure 3). The solenoid would automatically cease watering the plant when the soil moisture level reached the field capacity (28%).

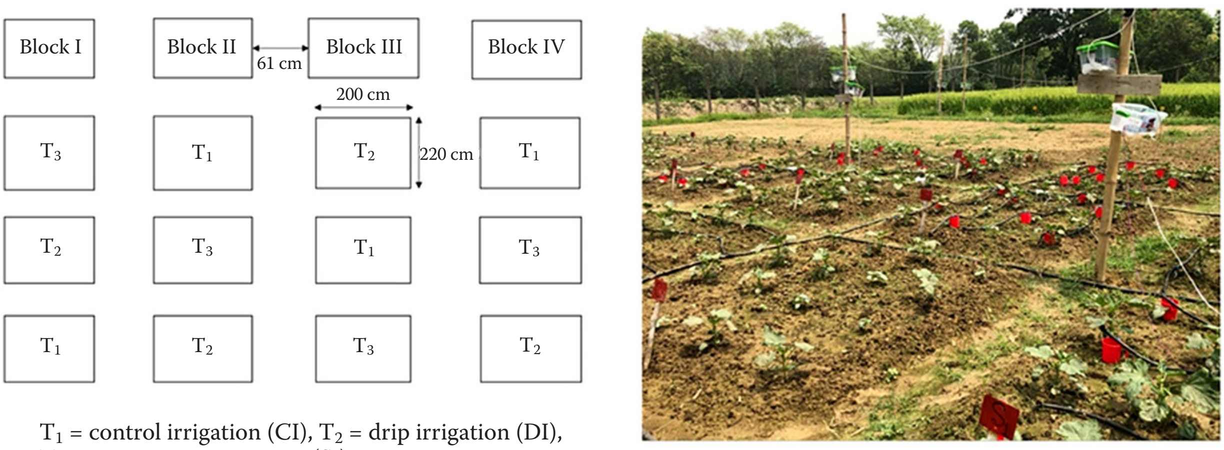
Experimental design

The experiment was arranged in a randomised complete block design (RCBD) with three treatments: T_1 = conventional irrigation (CI), T_2 = drip irrigation (DI), and T_3 = smart micro-irrigation (SI). The field was divided into four blocks to represent four replications of the treatments, with each block further subdivided into three treatment plots (Figure 4). The dimensions of each plot were 2 m × 2.2 m, and there was a spacing of 0.61 m between the adjacent blocks. Additionally, a 0.1 m buffer zone was maintained between the adjacent plots to facilitate movement within the plots.

Site and experimentation details

The experiment was conducted from March to May 2021 in the research field under the Department of Agricultural Engineering, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur, Bangladesh (Figure 5). The experiment site was situated at an altitude of 8.4 m a.s.l., with a latitude of 24°.09'N and a longitude of 90°.26'E. Meteorological data, including the rainfall, air temperature, relative humidity, and evaporation in the study area, were considered from the meteorological station located on the campus.

The experimental field falls within the Madhupur tract, characterised by silty clay loam soil with a pH



T_1 = control irrigation (CI), T_2 = drip irrigation (DI),
T_3 = smart microirrigation (SI)

In field evaluation on okra

Figure 4. Experimental layout of the okra field for the smart micro-irrigation system

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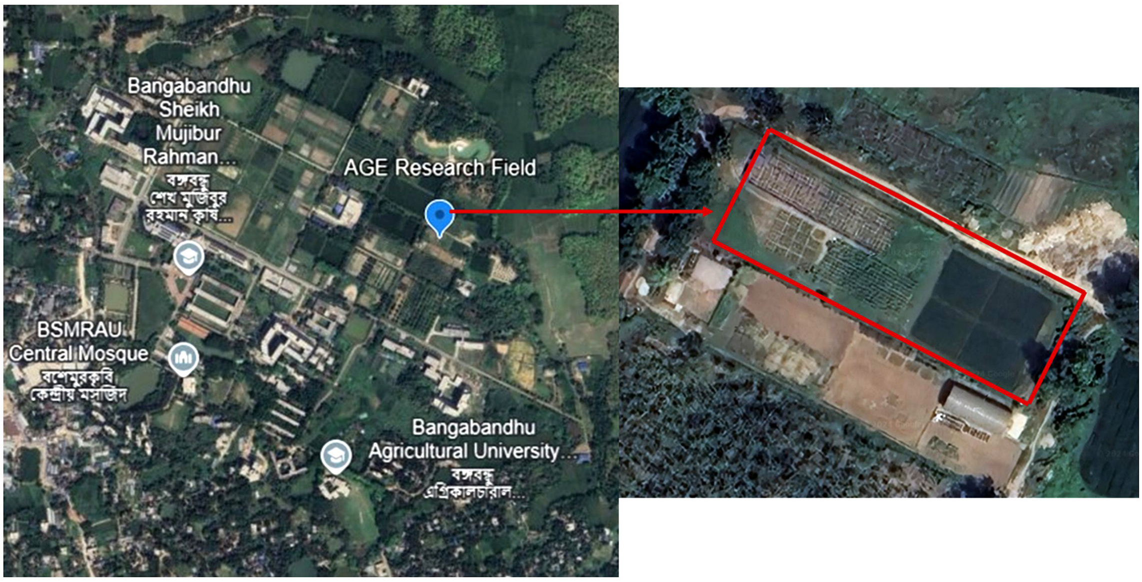

Figure 5. Experimental site in the research field of Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU)

of 6.3 within the top 0.5 m of the surface. For silty clay loam, the field capacity (*FC*) and permanent wilting point (*PWP*) were recorded at approximately 28% and 13%, respectively. The higher evapotranspiration of surface water indicates a need for more frequent irrigation. The optimal strategy for irrigating the crop field is to do so when the crop's rootzone reaches the management allowed deficit (*MAD*). In this experiment, we allowed for a 60% depletion of soil moisture before irrigation. *MAD* can be determined using Equation (1):

$$MAD = (FC\% - PWP\%) \times 0.6 \qquad (1)$$

where: *FC* – field capacity; *PWP* – permanent wilting point.

The land preparation involved multiple ploughing and cross-ploughing using a tractor to achieve proper tilth, along with the incorporation of well-decomposed cow dung. Each plot was elevated by approximately 0.1 m to form ridges from the soil surface. Okra (Kanchan) seeds, a high-yield variety developed by the United Seed Store, Bangladesh, were sown manually, taking around 5 days for germination. The row-to-row distance was maintained at 0.6 m, with a plant-to-plant distance of 0.4 m within each plot, and each plot had 16 holes (one seed per hole).

A low-head drip irrigation system was installed in the experimental plots, comprising a 20 mm main pipe connected to a 13 mm lateral pipe with online drippers. Positioned at a height of 1.5 m, a 1 000 L polyethylene water tank was controlled based on a pump controller (Zannat et al. 2023). One of the sets of the drip irrigation treatment (T_3) was integrated with a solenoid valve automatically controlled by soil moisture sensors and controllers, while another set of the irrigation treatment (T_2) was regulated with a manually controlled valve. A traditional flood irrigation method was applied to irrigate the okra field in the control treatment (T_1). A four-day interval irrigation schedule was maintained for the drip irrigation and control treatments, while the smart micro-irrigation treatment relied solely on the soil moisture conditions sensed by the soil moisture sensor. Intercultural operations were also performed diligently during the experimentation to promote the optimal growth of the okra plants and enhance the pod yield.

Drip performance evaluation

Flow measurement. The discharge rate of a dripper was determined by capturing the emitted water using 500 mL catch cans with known weights. These cans were placed under the laterals for a minimum period of 3 minutes (ISO 2004; Zannat et al. 2023). The collected water's equivalent volume was then used to calculate the hourly flow rate of the emitter, reported as litres per hour ($L \cdot h^{-1}$). The evaporation loss was adjusted with the flow rate dur-

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ing the weight measurement according to the ISO 9261:2004(E) protocol (ISO 2004).

Uniformity indices of drippers. The uniformity of the water application in micro-irrigation systems can vary significantly, and for the smooth execution of an experiment, a comprehensive uniformity index is essential. Several professional efforts have been made, as documented by Burt (2004), to evaluate uniformity indices. Of particular relevance for this study is the lower quarter distribution uniformity ($DU_{1/4}$). The calculation of the lower quarter distribution uniformity ($DU_{1/4}$) can be performed using Equation (2) established by Merriam and Keller (1978):

$$DU_{1/4} = 100\left(\frac{\bar{q}_{1/4}}{\bar{q}}\right) \quad (2)$$

where: $\bar{q}_{1/4}$ – average flow rate from the lowest quarter of the catch-can measurements ($L \cdot h^{-1}$); $\bar{q}$ – average flow rate from the total number of the catch-can measurements ($L \cdot h^{-1}$).

The emission uniformity (*EU*) of the drippers along the laterals was calculated using Equation (3), as per the guidelines outlined by ASABE (2006):

$$EU = 100(1 - CV) = 100\left(1 - \frac{SD_q}{\bar{q}}\right) \quad (3)$$

where: *CV* – coefficient of variance of the dripper discharge, which reflects the actual variation among the active drippers and fully clogged drippers must be excluded from the index; SD_q – standard deviation of the dripper flow rates.

Harvesting and data analysis

The initial harvest was conducted on April 28, 2021, followed by seven consecutive harvests. Data on the plant growth and yield contributions, including the plant height, number of leaves, days to first flowering, number of pods per plant, length of pod, number of seeds per pod, and overall yield, were recorded. Additionally, the crucial experiment parameter involved the application of irrigation water, and water savings were determined using Equations (4–7). The impact of each irrigation method on the growth, yield, and water usage of okra, as well as their interactions, was analysed using an analysis of variance (ANOVA) for the randomised complete block design (RCBD). Statistics software (Version 10, 2013) was employed for the analysis, with Tukey's HSD (honestly significant difference) used for the mean separation ($P \leq 0.05$).

Application of irrigation water. The total seasonal consumptive water use (*SCWU*) was determined by summing the total field irrigation water (*FIW*) applied using a 4-day interval irrigation schedule, the effective rainfall (R_e), and soil water contribution (*SWC*) between the sowing and final harvest. This calculation is expressed by Equation (5). The effective rainfall was estimated using the United States Department of Agriculture (USDA) soil conservation method, as described by Smith (1992).

$$SCWU = FIW + R_e \pm SWC \quad (4)$$

where: *SCWU* – seasonal consumptive water use; *FIW* – field irrigation water; R_e – effective rainfall; *SWC* – soil water contribution.

The soil water contribution was obtained by Equation (5):

$$SWC = \frac{M_p - M_h}{100} \times As \times D \quad (5)$$

where: M_p – soil moisture percentage at sowing; M_h – soil moisture percentage at harvesting; *As* – bulk density ($g \cdot cm^{-3}$); *D* – crop rootzone (cm).

The quantity of water savings was computed according to Equation (6):

$$\text{Water savings}(\%) = \frac{SCWU \text{ in CI} - SCWU \text{ in SI}}{SWU \text{ in CI}} \quad (6)$$

where: *SCWU* in CI – seasonal consumptive water use in the conventional irrigation (mm); *SCWU* in SI – seasonal consumptive water use in the smart micro-irrigation (mm).

Water use efficiency. The okra yield was computed after harvesting the crops, and the water use efficiency (*WUE*) for each irrigation treatment was calculated using Equation (7) described by Hillel (1997):

$$WUE = \frac{\text{Total marketable yield (kg)}}{\text{Total water used (m}^3\text{)}} \quad (7)$$

RESULTS AND DISCUSSION

Soil moisture calibration. The field capacity (*FC*) and permanent wilting point (*PWP*) were 28% and 13%, respectively. The management allowed deficit (*MAD*) was set to be 60%, and irrigation was started

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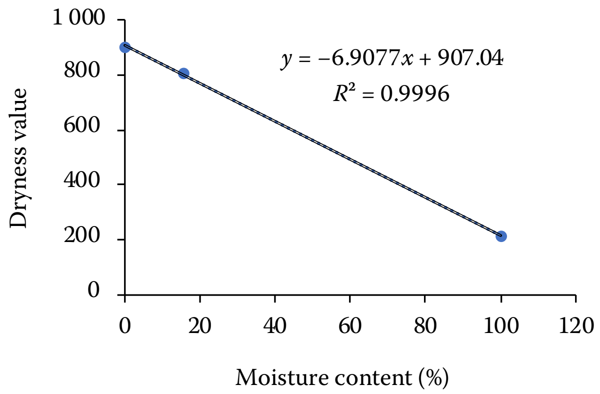

Figure 6. Calibration of the soil moisture from the graph

when the soil moisture reached 19%. In the experimental field, irrigation was started at 19% soil moisture and ended at an *FC* of 28%. For 19% and 28% soil moisture, the respective dryness values were used for the programming. The dryness value of the soil shown in the serial monitor was 820, while the weight of the wet sample with a ceramic cup was 68 g. The weight of the oven-dried sample with a ceramic cup was 59 g. The moisture content, calculated as (68 – 59)/59 × 100%, was determined to be 15.25%

Immediately after taking out the samples from the micro-oven, the soil moisture was measured to zero, and the dryness value of that sample was recorded to 900. Again, the samples were completely saturated with water, which indicated 100% soil moisture. The dryness value of that sample was measured to 215. These dryness values were used to create Figure 6 which is a calibration graph to interpolate any intermediate dryness levels. The graph revealed a dryness value of 775.79 for a soil moisture level of 19%, and a dryness value of 713.62 for the field capacity (*FC*) of 28%.

Performance evaluation of micro-irrigation system. The system's average flow rate (*q*) was calculated, and the emission uniformity (*SU*) was assessed to determine the consistency of the discharge from each dripper or the uniform distribution of water for each crop. According to ASABE (2006), the average emission uniformity for drip irrigation is 82.10%, falling within the 'good' category. In contrast, the average emission uniformity for the automated drip irrigation in the 'good' category was 80.13%, while the overall system's emission uniformity reached 81% (Table 1), which is also considered good according to ISO 9261. Notably, the manual drip systems exhibited an excellent average distribution uniformity of 86.63%, whereas the automated drip systems achieved a good distribution uniformity of 84.87%. The system's total lower quarter distribution consistency was 85.75%, qualifying it as being excellent according to the ASABE (2006).

Impact of the smart micro-irrigation system. In Table 2, the impacts of various irrigation treatments on the plant growth and yield components are detailed, essential for assessing their significant influence on the crop development. The highest average plant height (102.06 cm) was observed in T_3 (smart micro-irrigation), while the lowest height (94.12 cm) was found in T_1 (conventional irrigation). Despite slight variations, no significant differences among the treatments were noted, potentially due to the water being delivered directly to the rootzone of okra up to the field capacity. This result supports the idea that the supplied water was efficiently utilised under the smart micro-irrigation and drip irrigation, preventing water stress and promoting the proper physiological functions of the okra plants (Oshunsanya et al. 2016; Amoo et al. 2019).

The leaf number, assessed at the mature stage, revealed no significant differences among the treatments. T_2 exhibited the highest average leaves per plant (34.75), while T_1 showed the lowest (33.50). This aligns with the existing literature (Singh et al. 2005; Singh and Rajput 2007), suggesting that micro-irrigation methods can result in more branches and leaves, likely due to the varied carbon dioxide exchange rates and proper irrigation timings (Oshunsanya et al. 2016).

During the flowering stages, no significant differences were found among the treatments. T_3 exhibited the minimum days to first flowering (43.82),

Table 1. Drip performance evaluation for the micro-irrigation

Treatments	Flow rate *q* ± SD (L·h^{-1})	*CV* of flow rates	Average *EU* (%)	Lower quarter distribution uniformity (%)	Overall category
T_2	3.00 ± 0.52	0.175	82.10	86.63	good
T_3	3.06 ± 0.60	0.19	80.13	84.87	good

SD – standard deviation; *CV* – coefficient of variation ; *EU* – emission uniformity

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Table 2. Yield and yield-contributing characters of okra under the different irrigation treatments

Treatments	Plant height (cm)	No. of leaves per plant	Days of first flowering	No. of pods per plant	Length of pod (cm)	No. of seeds per pod	Yield ($t \cdot ha^{-1}$)
T_1	94.12^a	33.50^a	44.36^a	3.03^a	14.76^b	43.55^a	18.82^a
T_2	100.34^a	34.75^a	45.29^a	3.12^a	16.14^a	45.05^a	19.38^a
T_3	102.06^a	34.68^a	43.82^a	3.19^a	15.29^{ab}	40.15^a	19.63^a
CV	17.7261	1.5840	1.8538	1.1194	0.7480	10.0250	0.3022
HSD (0.05)	**	**	**	**	*	**	**

*significant differences among the means; **no significant differences among the means; *CV* – coefficient of variation; HSD – honest significant difference

while T_2 had the maximum (45.29). These results suggest that smart micro-irrigation reduces the water stress in okra plants, by regularly checking on the moisture status and watering the plants frequently. Since the irrigation frequency is increased, the soil moisture stress is inevitably reduced promoting increased flower propagation in the plant canopies (Jayapiratha et al. 2010).

The average number of pods per plant showed no significant pairwise differences among the means, but there was a significant difference in the pod length among the treatments (Table 2). T_2 achieved the highest average number of seeds per pod (45.05) compared to the other treatments, with no significant differences observed. The highest average pod yield (19.63 $t \cdot ha^{-1}$) was obtained in T_3, while the lowest (18.92 $t \cdot ha^{-1}$) was recorded in T_1. These results indicate no significant pairwise differences in the yield means among the irrigation techniques. Micro-irrigation is noted for maintaining moisture levels near the rootzone of okra plants, ensuring the available water and nutrients (Sharma et al. 2016; Zannat et al. 2023). This is how it maintains the yield compared to conventional continuous flooding systems while saving water.

Seasonal water use of okra. In Table 3, the seasonal water use of okra across the three treatments is presented, and the water use efficiency (*WUE*) findings serve as an indicator of the overall water productivity during the experiment. The highest *WUE* (15.34 $kg \cdot m^{-3}$) was observed in treatment T_3 (smart micro-irrigation), while the lowest *WUE* (12.97 $kg \cdot m^{-3}$) was found in treatment T_1 (conventional irrigation). These results highlight that the water productivity of the smart micro-irrigation system surpassed that of both drip and conventional irrigation. The varying water application methods across the treatments led to differences in the amount of water absorbed by the plants (Zannat et al. 2023).

The data suggests that the smart micro-irrigation (T_3) and drip irrigation (T_2) techniques saved an average of 13.10% and 8.26% (Table 3) of water, respectively, compared to conventional irrigation (T_1). These results suggest that the smart micro-irrigation system has the potential to conserve more irrigation water than both drip and conventional methods, as it allows for controlled watering based on soil dryness/wetness. However, it is noteworthy that the water savings observed under the smart micro-irrigation and drip irrigation are lower than those reported in the literature by Ibragimov et al. (2007), where approximately 18–42% of water savings were achieved under drip irrigation. A plausible explanation for this relatively modest water saving is the higher effective rainfall recorded (Table 3) during the period of okra production (March–May 2021).

Table 3. Seasonal water use of the okra under the three treatments during the experiment

Treatment	Total *FIW*	Effective rainfall	*SWC*	*SCWU*	Water use efficiency	Water savings
	(mm)				($kg \cdot m^{-3}$)	(%)
T_1	50.00	–	–105.00	145.00	12.97^a	–
T_2	38.25	200.00	–105.25	133.00	14.57^a	8.26
T_3	32.75	–	–106.75	126.00	15.98^a	13.10

FIW – field irrigation water; *SWC* – soil water contribution; *SCWU* – seasonal consumptive water use

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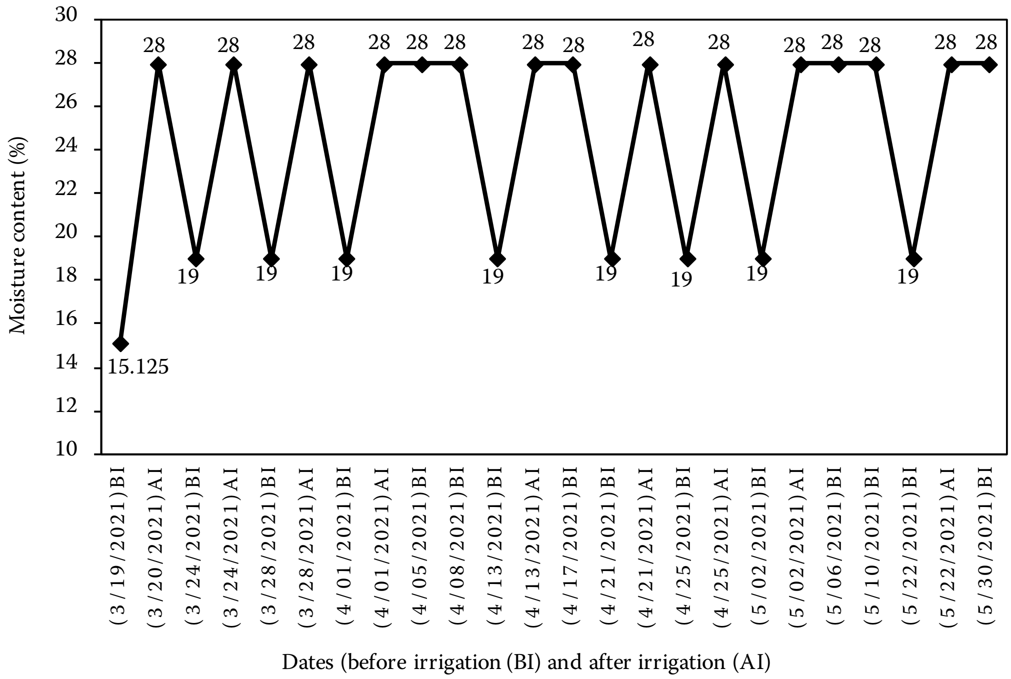

Figure 7. Soil-moisture graph before and after irrigation for the smart micro-irrigation

Soil-moisture level before and after irrigation. The initial soil water content in the okra field was found to be (15.125%) which remained the same up to a depth of 0.15 m below the ground. The smart micro-irrigation system was able to effectively maintain a moisture content of 19% before irrigation (Figure 7), as calculated, ensuring that the irrigation commenced at the appropriate times. The system also ensured that water would cease once the soil reached the field capacity (28%). The intermittent horizontal lines on the moisture graph represent the days when the irrigation was unnecessary due to ample rainfall, which sustained the soil moisture at field capacity levels. Both the yield and water savings were satisfactory, indicating that excessive moisture levels above 28% did not significantly contribute to the plant water uptake. Figure 7 serves as a valuable tool for decision-making, demonstrating the precision and reliability of the smart micro-irrigation system in managing soil moisture conditions.

Estimated cost for a smart micro-irrigation system. The estimated cost was calculated to determine the expenses involved in setting up a smart micro-irrigation system for an experimental field measuring 11.05 m × 9.04 m, accommodating 12 plots within a 100 m^2 area. A total of 192 drippers were installed in this drip irrigation system, with each plot equipped with 16 drippers. A main pipe spanning 61 m was necessary to convey the water from the water source to the experimental field, while lateral pipes extending 76.2 m were used to transport the water from the main pipe to the crop rootzones. Additionally, various miscellaneous connectors were required for the installation of the drip irrigation system.

Table 4. Estimated cost for building the smart micro-irrigation system for the experiment

Items of expenditure	Unit cost (EUR*)	Amount	Total (EUR*)
Smart irrigation-related cost			
Arduino Uno (microcontroller)	6.31	1	
Soil moisture sensor	14.56	1	
Relay module	2.91	1	33.97
Solenoid valve	7.28	1	
Jumper wire, cable and adaptor	2.91	LS	
Drip irrigation related cost			
Dripper (No.)	19.42	200	
Main pipe (m)	43.69	61	131.07
Lateral pipe (m)	48.54	76.2	
Miscellaneous connector	19.42	LS	
Labour + installation charges	4.85	–	4.85
Total			169.89

*EUR 1 = BDT 103 (as of May 2021); LS – lump sum

It can be observed from Table 4 that the cost of the manually operated drip installation was EUR 131.07 for this experiment. To upgrade to a smart micro-irrigation system, an additional EUR 33.97 will be required in addition to the cost of the drip irrigation system. Hence, the total installation cost of a smart micro-irrigation system is not significantly higher, making it an affordable option for users in Bangladesh.

CONCLUSION

The experimental results demonstrate the feasibility of employing a smart micro-irrigation system in an okra field. This system integrates a microcontroller, such as the Arduino Uno, with soil moisture sensors, solenoid valves, and a drip irrigation system. It enables the automated water flow in the okra field, eliminating the need for manual inspection and ensuring precise and secure irrigation. This smart system facilitates optimal plant development and production management, offering a high level of operational control. Throughout the experiment, no significant differences were observed among the treatments concerning the plant growth and yield, except for a slight variation in the pod length. The smart micro-irrigation system achieved the highest water use efficiency of 15.34 $kg \cdot m^{-3}$ which is 23.20% more than that of conventional irrigation treatment. These results suggest that the incorporation of a smart micro-irrigation system in an okra field can result in water savings of up to 13.10% when compared with the conventional irrigation practice.

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