Development and evaluation of wireless sensor network (WSN) based automated drip irrigation system under protected cultivation

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Abstract: Agriculture has significantly contributed to the socio-economic development and wellbeing of India. The automation and monitoring of water application in agriculture have enhanced productivity, efficiency, and performance in agricultural fields. This study presents the design, deployment, and field testing of a wireless sensor network–based automated drip irrigation system (DIS) for use in protected farming. The system has three nodes namely supervisory node, sensor node, and actuator node. The supervisory node serves as the primary controller of the system, determining the precise timing and quantity of water for crops. Sensor nodes collect data from various areas of the field and transmit it to the supervisory node. The actuator node consists of a solenoid valve that activates or deactivates based on the directives sent by the supervisory node. The efficacy of the developed WSN-based automatic DIS was assessed for tomato cultivation during two seasons in 2022. The system facilitated the administration of an ideal irrigation volume across the polyhouse, yielding higher emission uniformity, water distribution, and application efficiency rates of 91.55%, 94.91%, and 94.96%, respectively. The automated WSN based drip irrigation system applied weekly water ranging from 2.78 to 6.96 litres per tomato plant, achieving 21% reduction in water usage and 34.59% enhancement in tomato output compared to the manual DIS. The performance of the WSN-based automatic DIS surpassed to that of the manual DIS significantly in terms crop growth metrics and yield. Developed WSN-based DIS found efficient and suitable for organic vegetable cultivation with less human intervention.

Keywords: Agriculture, Drip irrigation, Hilly, Sensor, Protected cultivation, Tomato, WSN

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1 Introduction

Agriculture has played a crucial role in a socio-economic growth and welfare of India. In India, more

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than 70% of the population depend upon farm related activities and about 16% of the country’s GDP depends on agriculture (Kumar et al., 2019). Around 70% to 80% of the water is used in the agriculture sector. The rise in urbanization, globalization, and population has increased the water consumption in several sectors. Reducing water usage in agriculture while ensuring quality food production has become a major challenge for every country. To achieve higher yields, irrigation systems must continuously monitor key parameters such as temperature, soil moisture, and humidity—an essential requirement, especially in remote areas where water is scarce. Manually monitoring various plant parameters can be tedious; to address this, IoT-based technologies with automated monitoring and control systems (Khan et al., 2018) have proven to be highly efficient and productive. IoT provides diverse applications in various arenas namely health and medicine (Amin et al., 2018), road traffic control (Wang et al., 2010; Perera and Dias, 2011), security system (Kisseleff et al., 2014; Devasena and Sowmya, 2015), home/office automation (Çeltek et al., 2017; Abdulsalam et al., 2014), smart cities, and agriculture automation (Taebi et al., 2020; Wang et al., 2006). IoT is considered a vital solution in agriculture due to the sector’s need for continuous monitoring and control. The significant application of IoT in agriculture is in livestock, greenhouse (Zhao et al., 2010; Escamilla-Garcia et al., 2020) and precision agriculture (Zhang et al., 2002; Gebbers and Adamchuk, 2010) which can be supervised with the support of distinct IoT-based sensors/devices and utilizing wireless sensor networks (WSNs) that help the farmers to obtain corresponding information. Certain IoT-based WSNs uses cloud services (Piyare and Lee, 2013) for collection of data that can further be analyzed and processed to assist the researchers and farmers to make improved decisions. IoT-based technology for an automatic irrigation system can be used to save water, money, electricity, and time of the farmers. The system only supplies water when needed, preventing over-irrigation and reducing water waste. Since irrigation is automated, farmers save time otherwise spent manually operating pumps and valves. The optimized water use also reduces electricity costs for pumping. Overall, precise control of irrigation minimizes resource use, lowers operational costs, and increases efficiency for farmers (Xiao et al., 2013). IoT in agriculture can assist in data acquisition, proper water management, irrigation, weather condition and many more with minimum human interaction.

Wireless sensor network (WSN) usually consists of numerous multi-functional nodes that collect the basic data from soil, water, weather report to take an informed decision. These nodes consist of sensors, actuators, radio transceivers, microcontrollers (Gill and Chawla, 2021). Arduino (Dasgupta et al., 2019) and raspberry pi (Suciu et al., 2019) are one of the widely used microcontrollers for automation in agriculture. Actuators for irrigation include solenoid valve (Raut et al., 2018; Qi et al., 2017), sprinklers (Wasson et al., 2017; Singh et al., 2019) and so on. Gutiérrez et al. (2013) developed solar powered automated irrigation using WSN and GPRS modules. Data inspection was monitored with help of the duplex communication link based on a cellular Internet interface. Zigbee was used for implementing WSN, where the data is monitored remotely supervised online through a graphical application via gadgets with availability of an internet. Avatade and Dhanure (2015) developed an automated irrigation system based on an ARM microcontroller having a wireless sensor unit and a wireless information unit. They reported that developed system diminishes the use of water & in return optimizes agricultural production. Singh and Saikia (2016) designed an arduino-based automatic smart sprinkler irrigation system. The moisture, temperature, and amount of water required by the crops were collected through sensors. They reported that the developed system could be implemented in a large area by the website communication, which assists the farmer to yield quality crops. Palande et al. (2018) designed an automated hydroponic system for an indoor plant that used different sensors to measure pH level of water, water temperature and CO_2. They found that the plant monitored using IoT based system had better results than the plant that was not kept in the system. Mekala and Viswanathan (2019) used IoT techniques to measure the humidity and temperature of a crop. Summarizing review of some studies conducted on use the sensors and IoT platform for agricultural and allied field including smart water management, irrigation, hydroponics and precision agriculture etc. are presented in Table 1.

Above studies carried out at several locations and field conditions, show the future adaptability of IoT-based automated irrigation management technique for climate smart agriculture. Protected cultivation is one of the prominent practices where crops are cultivated under fully controlled or partially controlled environment. Significance of greenhouse monitoring and control with support of IoT and WSN can increase the quantity and quality of produce (Tzounis et al., 2017).

The present study was conducted in the hilly state of Sikkim, India. Declared the country's first organic state in 2016, Sikkim's farmers cultivate horticultural crops, vegetables, fruits, and flowers using organic farming practices. One of the major challenges for farmers in hilly regions is the rough terrain, which makes accessing fields difficult. To address this, a soil moisture sensor–based automated drip irrigation system using a WSN was developed for protected environments, providing a practical solution for remotely located hill farmers. Although India has extensive internet and network coverage, certain areas in Sikkim still face connectivity issues. To overcome this, the system utilizes radio-frequency protocols, making it highly beneficial for farmers in the hilly regions of Sikkim.

2 Materials and methods

2.1 Study field

The study was conducted inside the bamboo-structured polyhouse located in the experimental field of the College of Agricultural Engineering and Post Harvest Technology (CAEPHT), East Sikkim, India. The study site is located at 27°17.28′ N latitude and 88°35.49′ E longitude, with an elevation of 878 m above mean sea level (Figure 1). A WSN-based automated drip irrigation system (DIS) was designed and installed within an area of 75 m². The soil texture of the study area is sandy loam, with mean percentages of sand, silt, and clay at 74.0%, 15.0%, and 11.0%, respectively. The mean bulk density (BD) and particle density (PD) are 1.57 g cm^{-3} and 2.57 g cm^{-3}, respectively. The annual rainfall ranges from 2300 to 2500 mm, with the southwest monsoon contributing approximately 78.44% of the total annual precipitation.

Table 1 Applications of IoT in agriculture, precision farming, smart water management

Sl. No.	Applications of IoT in agriculture	References
1	Theme: Irrigation water management	
	Smart sensors, valves, pumps and IoT based irrigation systems for sustainable agriculture	Abayomi-Alli et. al. (2018); Dasgupta et al. (2019); Debauche (2018); Gutiérrez et al. (2013); Imteaj et al. (2016); Jain (2023); Khan et al. (2018); Srinivas et al. (2022); Vaishali et al. (2017); Wang et al. (2020); Ali et al. (2019); Nawandar and Satpute (2019).
2	Theme: Hydroponic cultivation	
	IoT based automation for hydroponic management and monitoring	Crisnapati et al. (2017); Saha (2021); Sudharsan et al. (2019)
3	Theme: soil health management	
	Soil quality and soil environment monitoring system	Deng (2020); Guruprasadh et al. (2017); Xiao et al. (2013)
4	Theme: Greenhouse cultivation	
	IoT based greenhouse automation and monitoring system	Ardiansah et al. (2020); Fajrin et al. (2018); González-Amarillo et al. (2018); Hassan et al. (2015).
5	Theme: Precision agriculture	
	IoT based precision agriculture and smart agriculture	Gondchawar and Kawitkar (2016); Jawad et al. (2017); Khattab et al. (2016); Suciu et al. (2019); Zamora-Izquierdo et al. (2019); Patokar and Gohokar (2018).

Figure 1 Location map of study area

2.2 Design and development of WSN based drip irrigation system

The developed system mainly includes three important nodes that comprise a sensor node, actuator node and supervisory node. The framework of IoT-based automated system is shown in Figure 2.

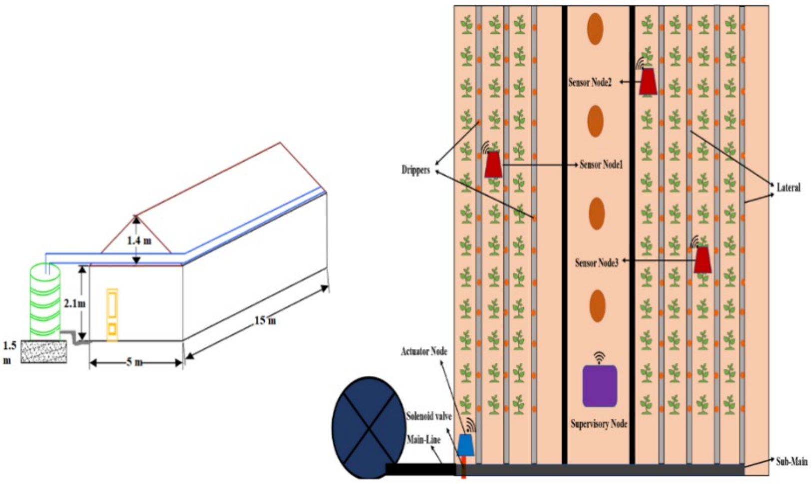


Figure 2 Framework of developed IoT system

The block diagram illustrating the implementation of the WSN-based automated drip irrigation system for polyhouse farming is shown in Figure 3. The system architecture consists of three primary nodes: the supervisory node, the actuator node, and the sensor nodes. The supervisory node was equipped with an nRF24L01 transceiver module, an Arduino Mega microcontroller, an SD card for data storage, an LCD display, and a real-time clock (RTC) module. The sensor network comprised three sensor nodes, each integrating a capacitive soil moisture sensor, an Arduino Nano controller, and an nRF24L01 transceiver module. The actuator node consists of a solenoid valve controlled by an Arduino Nano and interfaced with an nRF24L01 transceiver module. Each node was assigned a unique address to facilitate communication: the supervisory node was assigned address ‘00’; the sensor nodes were assigned addresses ‘01’, ‘02’, and ‘03’; and the actuator node was assigned address ‘04’ (Figure 4). The supervisory node served as the central control unit, periodically transmitting requests to all three sensor nodes at two-minute intervals, independent of the time of day. Upon receiving these requests, the sensor nodes transmitted soil moisture data, which were logged onto the SD card along with the corresponding node address. The solenoid valve operation was scheduled within predefined irrigation windows of 09:00–12:00 and 15:00–18:00. During these intervals, the supervisory node not only collected sensor data but also executed control commands for irrigation. When the average soil moisture value reported by the sensor nodes dropped below a predetermined threshold, the supervisory node activated the actuator node to open the solenoid valve. Conversely, when the measured values exceeded the threshold, a signal was sent to close the valve. The recorded data was stored on the SD card and subsequently be utilized for detailed analysis of soil parameters and system performance evaluation.

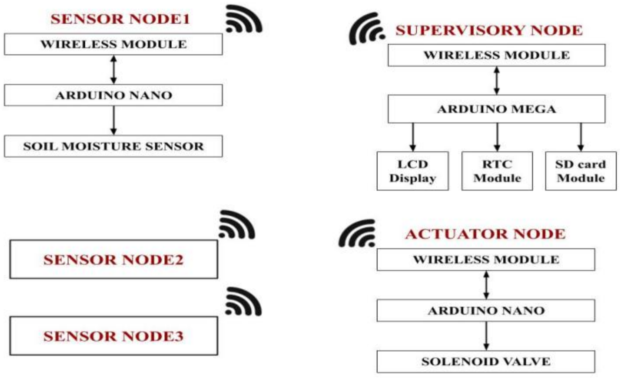


Figure 3 Block diagram of implemented system

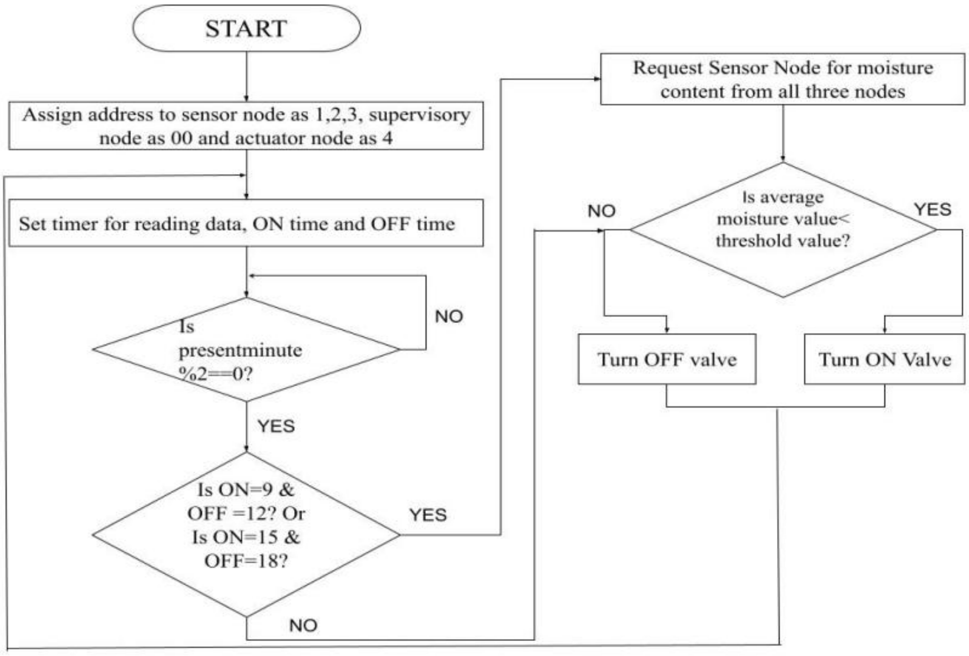


Figure 4 Flow chart that shows how the system works

2.3 Schematic diagram

The proposed IoT-based irrigation system consisted of an integration of hardware, software, and IoT components. The hardware included two main microcontrollers, Arduino Nano and Arduino Mega, which functioned as the sensor node, supervisory node, and actuator node.

2.3.1 Supervisory node

For supervisory node the NRF module (Palande et al., 2018), SD-card module, RTC chip module LCD Display was connected to arduino mega (Zamora-Izquierdo et al., 2019). The NRF24L01 was connected through SPI pin where it uses MISO, MOSI, SCN, SCK, CE, VCC (3.3 VDC) and GND (0) as shown in Figure 5. This node was responsible for controlling the sensor, carrying out communication protocol and processing the algorithm of the sensing data.

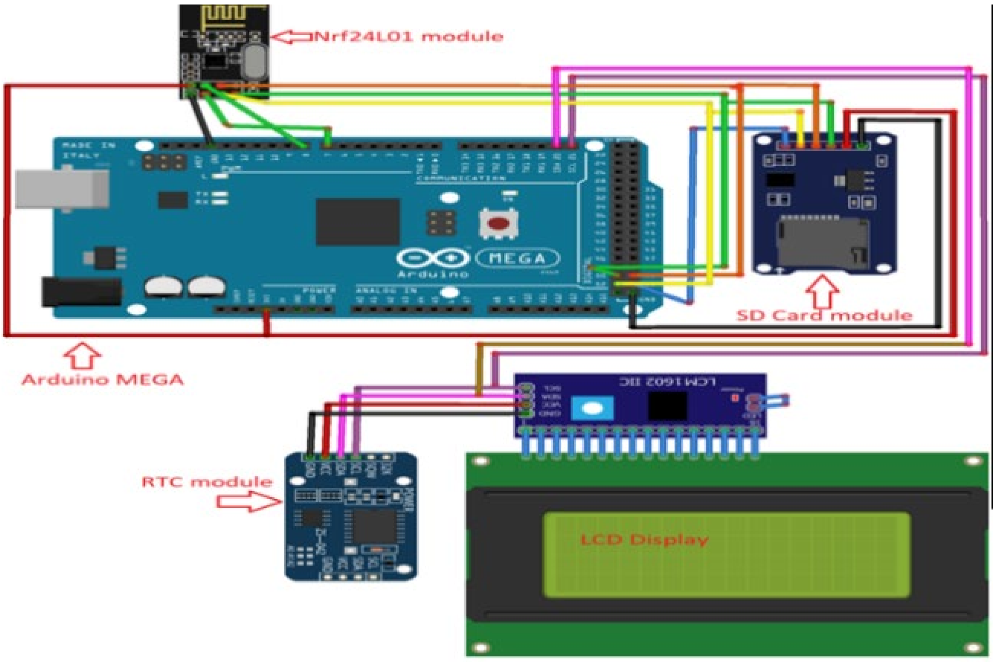


Figure 5 Schematic diagram of supervisory node

2.3.2 Sensor node

The sensor node of the WSN differed from a conventional sensor in its functionality. It not only detected variations in the measured physical quantity and generated corresponding output data, but also incorporated remote communication capabilities similar to those of an intelligent sensor. The node consisted of an NRF24L01 module, a soil moisture sensor, and a 4-digit display, all interfaced with an Arduino Nano. The soil moisture sensor was connected to the analog pin A0 of the Arduino Nano, and the entire sensor node operated on a 5V DC power supply, as illustrated in Figure 6. The NRF24L01 module utilized the same SPI pin configuration as the supervisory node to enable wireless communication. Upon receiving a request from the supervisory node, the soil moisture sensor collected soil data and transmitted it to the supervisory node via the NRF24L01 transceiver.

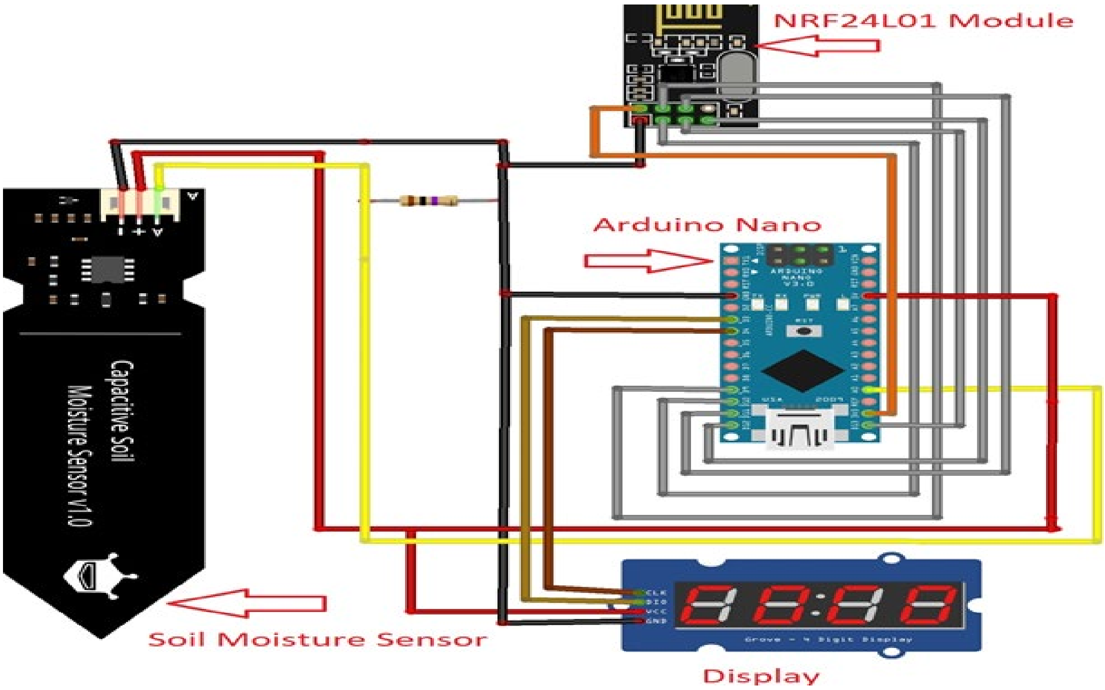


Figure 6 Schematic diagram of sensor node

2.3.3 Actuator Node

The actuator node consisted of a relay and an NRF24L01 module interfaced with an Arduino Nano (Figure 7). When the supervisory node detected that the soil moisture content was either above or below the threshold value, it triggered the actuator node to switch the relay ON or OFF. The relay, in turn, controlled the solenoid valve to regulate irrigation by opening or closing the water flow accordingly.

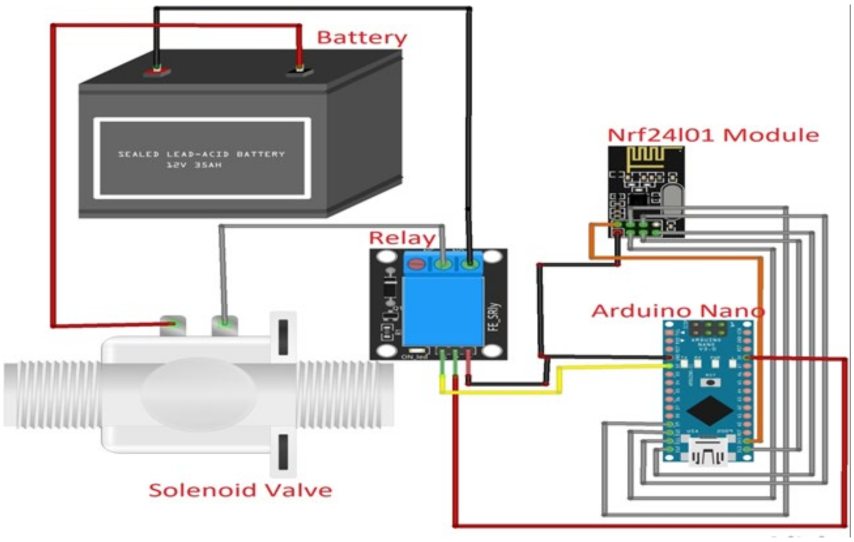


Figure 7 Schematic diagram of actuator node

3 Results and discussion

The developed WSN based micro controller was deployed in the bamboo structure polyhouse and connected with drip-irrigation system for its performance evaluation. The WSN based automated drip irrigation system was evaluated for tomato crop planted inside the polyhouse. The results were compared with the manual drip irrigation and WSN based automated drip irrigation. The WSN-based system primarily facilitated communication among three nodes: the actuator node, supervisory node, and sensor nodes. The sensor nodes were strategically deployed within the polyhouse to continuously monitor soil moisture using capacitive sensors positioned near the tomato crop root zone. The drip irrigation system was evaluated for its hydraulic performance inside the polyhouse. Discharges from the emitters were collected adopting the standard procedure explained by Mane et al. (2008). The results of the hydraulic parameters are presented in Table 2. The coefficient of variation (C_V), emission uniformity (*EU*), distribution efficiency, and application efficiency were found to be 0.051%, 91.55%, 94.91%, and 94.96%, respectively, while the emitter flow variation was 10.20%. These results indicated good performance of the installed drip irrigation system, meeting all the design considerations for such systems.

Table 2 Hydraulic evaluation of WSN based drip-irrigation system

Sl. No.	Particulars	Formula	Results
	Coefficient of variation, C_V	$C_v = \frac{s}{q_{avg}}$	0.051
	Emission uniformity, *EU* (%)	$EU = 100\left(1 - \frac{1.27}{N_e 0.5} C_v\right)(\frac{q_{min}}{q_{avg}})$	91.55%
	Emitter flow variation, Q_{var}	$Q_{var} = 100(1 - \frac{q_{min}}{q_{max}})$	10.20
	Distribution efficiency, E_d (%)	$E_d = 100(1 - \frac{\Delta q_a}{q_m})$	94.91%
	Application efficiency, E_a (%)	$E_a = 100(\frac{N. q_{min}. T}{V_w})$	94.96%

Where,

s = standard deviation (lph);

q_{avg} = average flow of the drippers (lph);

N_e = number of point source emitter per emission point source;

q_{min} = minimum flow rate in system (lph);

q_{max}= maximum flow rate in system (lph);

q_x= average of the highest 1/8th emitter discharge (lph);

V_q= coefficient of variation of emitter flow;

Δq_a= average absolute deviation of each emitter flow from the mean emitter flow;

q_m= mean emitter flow rate (lph);

N= total number of emitters;

V_w= total volume of water applied (l);

T= total irrigation time (h).

3.1 Calibration of soil moisture sensor

The sensor node was equipped with a capacitive soil moisture sensor that collected soil moisture data and transmitted the information to the supervisory node (Figure 8). The data obtained from the capacitive sensor were used to control the solenoid valve, which was automatically opened or closed based on the predefined threshold values. Initially capacitive soil moisture sensor was calibrated with respect to the soil moisture data obtained by oven drying method. The calibrated readings of the capacitive soil moisture sensor are presented in Table 3. Sensor values below 210 represented very wet field conditions, values between 250 and 280 indicated normal soil moisture levels sufficient for plant growth without stress, and values exceeding 300 represented dry field conditions.

Table 3 Calibrated capacitive soil moisture sensor value

Moisture value of the sensor	Class
<210	Very wet
250-280	Normal
>300	Dry

Figure 8 shows the graph of the capacitive soil moisture sensor, which measured the dielectric permittivity of the surrounding soil that varied with water content. The sensor provided an analog output corresponding to the soil's moisture level. Over time, the sensor values fluctuated with changes in soil moisture content, and these data were used to control the irrigation process.

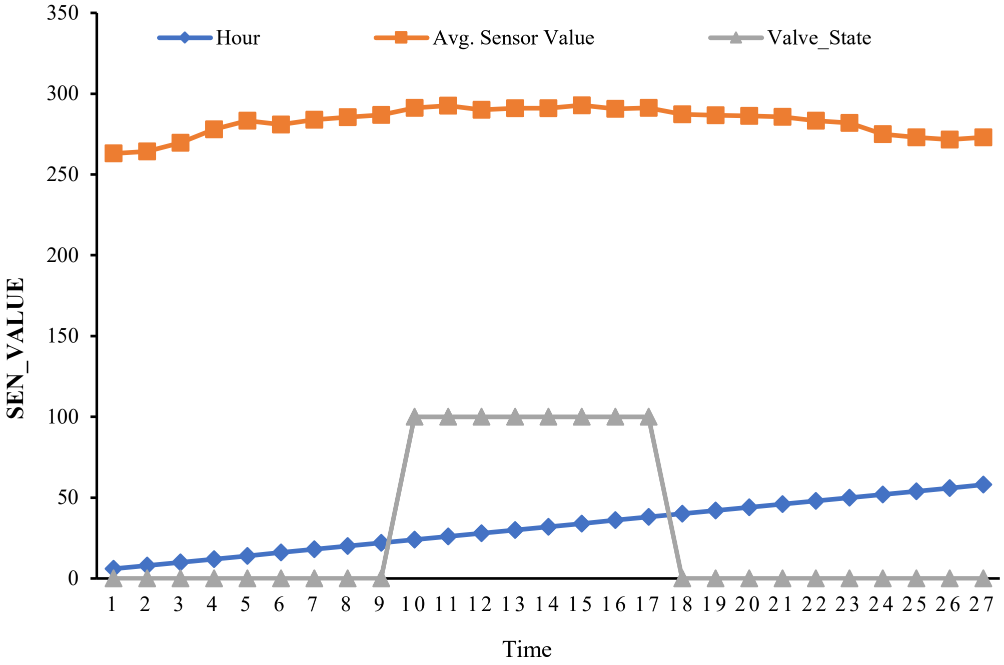


Figure 8 Graph of capacitive soil moisture sensor

It was observed from the graph that the soil moisture content gradually decreased over time, resulting in an upward trend in the curve. The actuator node incorporated a solenoid valve connected to the main water tank. When the sensor reading reached a predefined threshold, the valve was activated for a specified duration, as shown in the graph. Once the sensor value dropped below the threshold, the valve was deactivated, thereby stopping the water flow.

Table 4 presents the average readings of the capacitive soil moisture sensors from three different sensor nodes. By integrating time, sensor values, and solenoid valve status, the system ensured efficient water usage. The valve was opened when the threshold value reached 0 or 1, based on real-time sensor data, predefined conditions, and optimized irrigation management. The recorded data demonstrated the system's ability to provide flexibility and efficiency, minimizing water wastage while ensuring that crops received adequate water according to actual soil conditions.

Table 4 Sensed soil moisture data and state of valve

Sl. No	Time (h)	Sensor value	State of valve
	15:00	263.0	0
	15:02	264.3	0
	15:04	269.7	0
	15:06	277.9	0
	15:08	283.3	0
	15:10	286.8	0
	15:12	291.2	1
	15:14	292.7	1
	15:16	290.0	1
	15:18	290.9	1
	15:20	291.0	1
	15:22	292.9	1
	15:24	290.7	1
	15:26	287.3	0
	15:28	286.7	0
	15:30	286.3	0
	15:32	285.7	0
	15:34	278.0	0

Figure 9 Complete set-up of the system in polyhouse

The complete setup of the system within the naturally ventilated polyhouse for tomato cultivation is shown in Figure 9, representing three sensor nodes (a, b, and c), the supervisory node (d), the actuator node (e), and the connected solenoid valve (f). The average capacitive soil moisture sensor values from the three sensor nodes, analyzed over a span of five weeks are presented in Table 5. Figure 10 illustrated the graphical representation of these values. As shown in Figure 10, the average soil moisture values increased over time, indicating a gradual drying of the soil, consistent with the calibrated sensor values outlined in Table 3. When the average sensor reading exceeded 290, the solenoid valve was automatically activated, resulting in a gradual decrease in the graph as irrigation occurred. Conversely, when the average value dropped below 290, the valve was turned off, allowing the soil to dry, which caused the sensor readings to rise again. This pattern produced a continuously decreasing curve during irrigation periods and an increasing curve as the soil dried over time. The supervisory node not only stored all sensor data on the SD card but also controlled the actuator node, demonstrating the system's ability to operate autonomously. Thus, the system functioned effectively in automatic mode, validating its potential as a smart irrigation solution.

Table 5 Sensed soil moisture data for span of 5 week

Week	Average sensor value
week 1	291.84
week 2	289.28
week 3	289.01
week 4	281.88
week 5	282.84

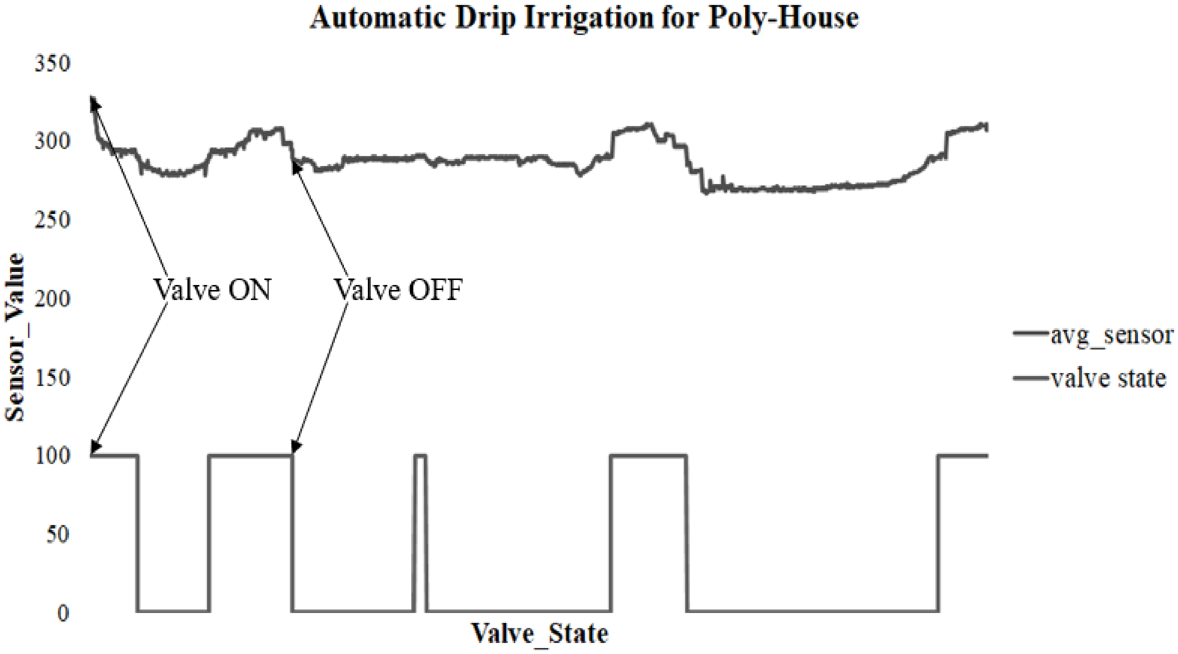


Figure 10 Graph of capacitive soil moisture sensor

3.2 Performance of Tomato crop

The calibrated soil moisture sensor-based automated drip irrigation system using a WSN was evaluated for tomato crop performance over a 110-day growing period under a naturally ventilated polyhouse. Tomato plants of the variety *Arka Rakshak* were transplanted inside the polyhouse with a spacing of 60 cm × 75 cm. Raised beds were prepared on both sides of the polyhouse, and 16 mm diameter laterals equipped with 2 lph pressure-compensating drippers were installed to deliver irrigation water directly to the root zone. For comparative analysis, an adjacent open field plot of 15 m² (3 m × 5 m) was prepared and planted with the same tomato variety. While the polyhouse crop was irrigated using the automated sensor-based drip irrigation system, the open-field crop was irrigated manually using a conventional drip system. Irrigation performance was monitored over a 10-week period following transplanting. The volume of water applied through both systems is shown in Figure 11. In the open field, the weekly water requirement ranged from 3.5 to 8.89 liters per plant per day. In contrast, the automated system applied between 2.78 and 6.96 liters per plant per day during the same period. Over the 10-week monitoring period, the total water consumption by the sensor-based automated drip irrigation system was 49.76 liters per plant approximately 21% less than the manually operated system. Visual observations of crop development inside the polyhouse revealed healthy growth and fruit formation. Figure 12 illustrates (a) the initial stage of fruit development, (b) the installed system inside the polyhouse, (c) maturing fruit on the plant, and (d) fully ripened fruit at harvest.

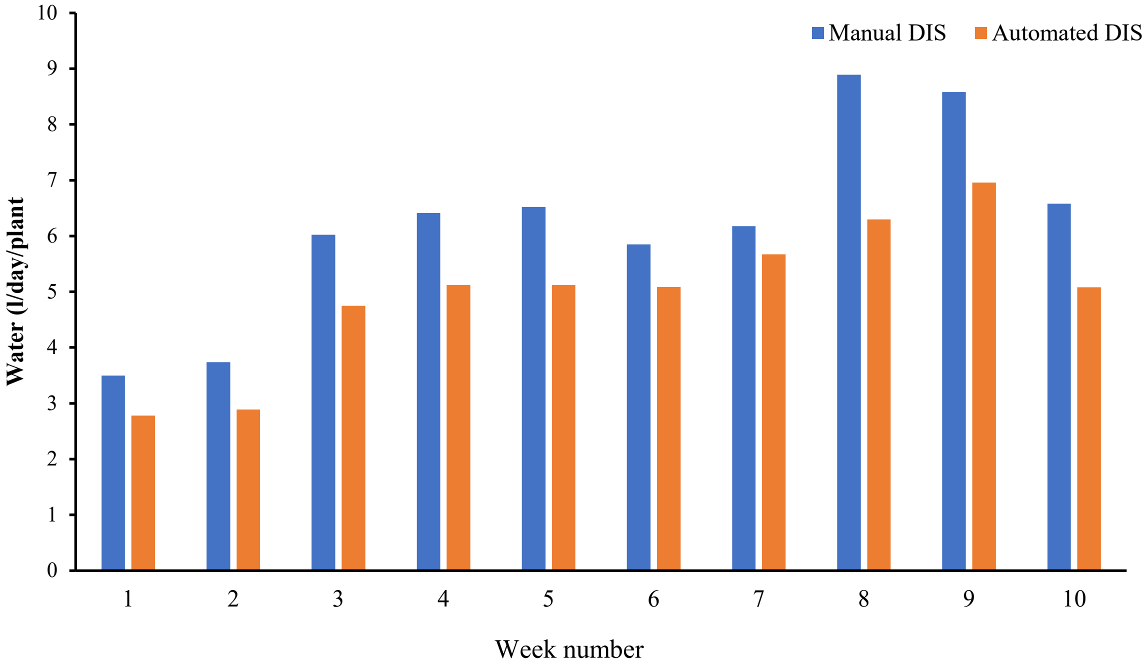
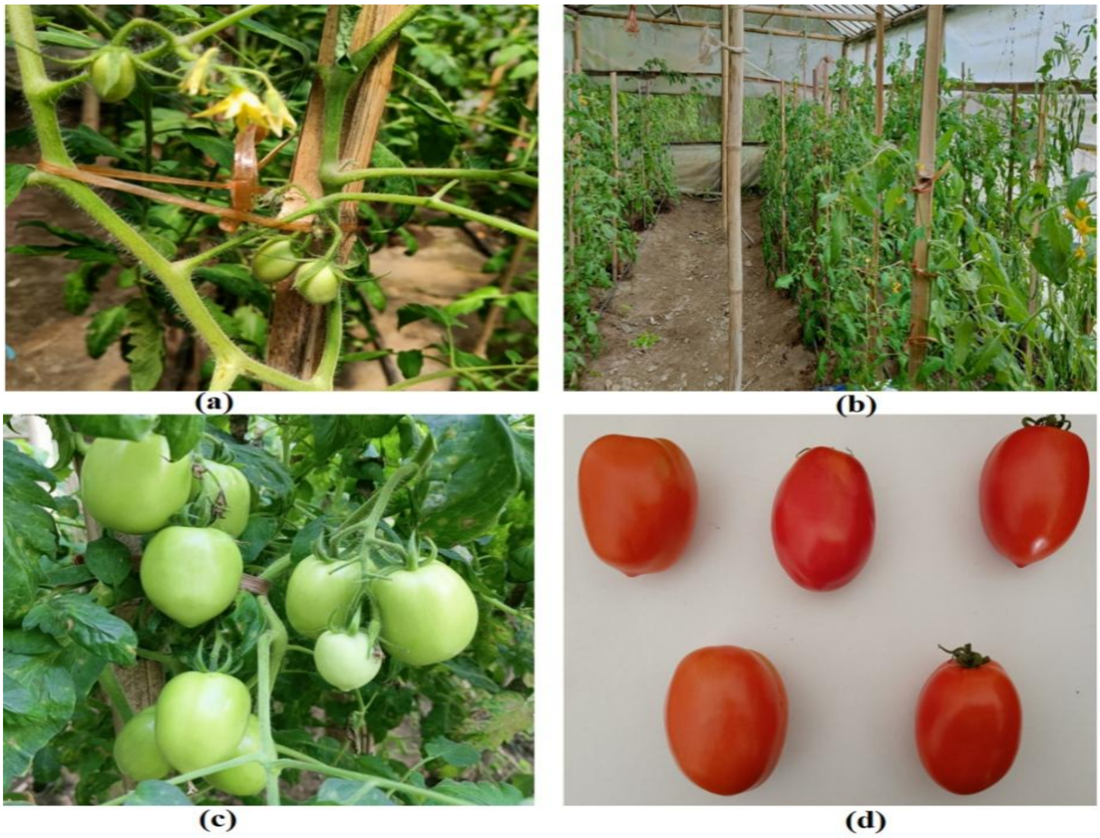


Figure 11 Comparison of water applied through automated DIS and Manual DIS



(a) initial stage of fruit, (b) system placed inside the green house, (c) fruits on the plant, d. final ripped fruit

Figure12 Growth of tomato plant place inside the green-house

3.3 Comparative performance of tomato growth parameters

Tomato crop growth parameters namely plant height, canopy spread, stem diameter, and number of leaves were measured and recorded at regular 12-day intervals using standard procedures for both polyhouse (automated drip irrigation) and open field (manual drip irrigation) conditions. The results are presented in Table 6. The automated irrigation system had a significant influence on key growth indicators, including plant height, canopy size, stem diameter, number of leaves, and average number of fruits per plant. For instance, on day 24 after transplanting, the difference in plant height between treatments was 15.91 cm, which exceeded the critical difference (CD) value, indicating a statistically significant improvement under automated drip irrigation. This demonstrated that the automated system provided more favorable conditions for tomato growth compared to the manual drip system. As shown in Table 6, both irrigation methods showed similar performance during the initial stages of growth. However, as the growing period progressed, plants irrigated with the automated system consistently outperformed those under manual drip irrigation across most growth parameters. Additionally, improvements were observed in fruit yield and fruit size under automated conditions. The recorded tomato yield under the automated drip irrigation system was 3.70 kg m^{-2}, compared to 2.42 kg m^{-2} for the manually irrigated open-field crop. This represented a 34.59% increase in yield due to the use of the automated system.

Table 6 Statistical analysis of biometric crop growth parameters of Tomato crop

Days	Day 1	Day 12	Day 24	Day 36	Day 48	Day 60	Day 72	Day 84
Mean plant height (cm)								
Drip(Automatic)	39.82	61.86	117.18	151.45	175.09	200.90	207.727	224.02
Drip(Manual)	37.09	60.72	101.27	132.54	157.63	173.81	185.91	199.15
CD	N/A	N/A	14.256	14.603	15.447	17.396	12.573	11.111
Mean plant canopy (cm)								
Drip(Automatic)	41.63	47.64	80.27	103.00	116.54	128.36	138.72	150.81
Drip(Manual)	43.63	49.72	71.45	91.27	100.45	109.45	115.18	121.45
CD	N/A	N/A	5.852	7.627	7.892	8.849	8.364	7.543
Mean stem diameter (mm)								
Drip(Automatic)	4.22	5.01	6.09	6.97	7.55	8.02	8.78	9.32
Drip(Manual)	4.40	5.16	6.04	6.49	7.06	7.32	7.58	7.74
CD	N/A	N/A	N/A	0.457	N/A	0.622	N/A	0.712
Mean number of leaves								
Drip(Automatic)	5.72	11.09	18.54	22.90	28.45	32.81	39.72	49.36
Drip(Manual)	5.54	9.36	13.45	16.45	20.90	25.36	29.72	35.45
CD	N/A	1.294	2.327	2.46	3.38	2.958	2.828	3.298

	Number of fruits/ Yield
Drip(Automatic)	53
Drip(Manual)	41
CD	4.48

Thus, the automated drip irrigation system implemented under a protected environment resulted in both significant water savings and increased tomato yield. These outcomes can be attributed to the system's ability to deliver water in real time and with high precision, maintaining optimal soil moisture levels throughout the crop growth period. Tomato plants are highly sensitive to water stress, and several studies have demonstrated that maintaining ideal soil moisture levels leads to improved growth and yield performance (Yang et al., 2016). The automated system minimized the risks associated with over-irrigation, such as nutrient leaching, by regulating water application accurately based on sensor feedback. These findings are consistent with those reported in previous studies on sensor- and IoT-based smart irrigation systems (Avatade and Dhanure, 2015; Ali et al., 2019; Nawandar and Satpute, 2019; Srinivas et al., 2022), which also highlighted improvements in water use efficiency and crop productivity under automated irrigation regimes.

The IoT-based automated drip irrigation system developed for polyhouse cultivation was found to be both feasible and cost-effective (Table 7), offering significant time savings and ensuring optimal water usage for agricultural purposes. The estimated cost of the system was approximately Rs. 8000/-, making it affordable for small and medium-scale farmers. The system successfully addressed limitations observed in earlier models, such as limited communication range and connectivity issues, as noted by Patle and Sherpa (2022). In rural areas of Sikkim, where internet access is limited and conventional network infrastructure is often unavailable, the use of the NRF24L01 module proved to be an effective solution. With a communication range of up to 1 km, the module was suitable for typical farm sizes in the region, enabling reliable data transmission between nodes. The entire system operated using Arduino Nano and Arduino Mega microcontrollers, which interfaced with wireless modules to facilitate seamless data exchange. The system was capable of functioning with minimal human intervention, providing irrigation only when the soil moisture level fell below a predefined threshold. By delivering water directly to the root zone, the system enhanced water use efficiency and maintained a more consistent soil moisture-to-root ratio. Overall, the system demonstrated high efficiency, compatibility, and adaptability to various crop requirements. It required minimal maintenance and found well-suited for deployment in remote agricultural settings. Given its simplicity, affordability, and effectiveness, the system showed strong potential for adoption by farmers in similar agro-climatic regions.

Table 7 Major components with specifications used in development of system

Sl. No.	Parts	Quantity	Specification
	Arduino	5	Mega 2560 & Nano
	Radio communication device	5	NRF24l01(1.9 to 3.6 V)
	RTC module	1	DS3231 (2.3-5.5 V)
	SD-Card and module	1	3.3-5 V
	LCD display	1	16X4
	Power Bank	5	20k mAh
	Soil moisture sensor	3	Capacitive SMS V2.0
	Relay module	1	5V
	Lead acid Battery	1	12 V DC
	Solenoid valve	1	12 V DC

4 Conclusion

Advancements in smart farming technologies have demonstrated that automated approaches to irrigation and water management are both cost-effective and efficient. This study focused on the development and field evaluation of a low-cost WSN-based automated drip irrigation system for organically cultivated tomato crops in the hilly regions of Sikkim. Conventional drip irrigation in these regions, often controlled manually, demands significant labor and leads to inefficient water use, especially in areas with difficult terrain. The developed system addressed these challenges by enabling real-time, sensor-based water application tailored to soil moisture conditions. Field results confirmed a 21% reduction in water use and a 34% increase in tomato yield compared to manually operated drip irrigation systems. These outcomes highlight the system’s effectiveness in promoting water conservation, improving crop productivity, and reducing labor requirements. The WSN-based solution is adaptable, low-maintenance, and well-suited for protected cultivation and remote agricultural areas. Future enhancements, such as integrating image processing for early disease detection, could further expand the system's utility in precision agriculture.

Data Availability

Data shall be available on request.

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Conflict of Interest

Authors declare no conflict of interest.

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