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Microcontroller-based smart irrigation systems: a review of sensor integration, automatic control, and water management

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ABSTRACT

Smart irrigation systems provide an effective approach to improving agricultural water management through sensing, automation, and remote monitoring. This review examines microcontroller-based smart irrigation applications, with particular attention to soil moisture measurement, actuator control, internet of things (IoT) communication, and intelligent irrigation scheduling. Previous studies demonstrate that low-cost platforms such as Arduino can acquire environmental data and operate pumps or valves according to predefined soil-moisture thresholds. More advanced systems extend these functions through cloud services, wireless communication, weather information, and machine-learning methods. The review compares representative implementations published up to 2019 and discusses their hardware architectures, communication approaches, energy options, and operational capabilities. It also considers practical challenges, including sensor calibration, network reliability, power availability, installation costs, and system maintenance. Evidence from the reviewed studies indicates that microcontrollers remain suitable for small and medium-scale irrigation automation because they are inexpensive, accessible, and adaptable to different agricultural conditions. However, successful deployment requires appropriate sensor placement, reliable control logic, and evaluation under actual field conditions. The review concludes by identifying design considerations for developing affordable, scalable, and resource-efficient smart irrigation systems locally.

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1. INTRODUCTION

Agriculture requires reliable water management to maintain crop growth and productivity. Conventional irrigation practices often depend on manual observation and fixed watering schedules, which may result in excessive or insufficient water application. These limitations have encouraged the development of automated irrigation systems that use sensors and electronic controllers to make irrigation decisions according to field conditions.

Microcontrollers are important components in these systems because they can process sensor measurements and control irrigation equipment. A microcontroller-based system can receive information from soil moisture sensors, compare the measurements with predefined conditions, and activate a pump or valve when irrigation is required. Rawal [1] demonstrated an automated irrigation approach using an ATmega328P microcontroller on an Arduino Uno platform, with soil moisture sensing and Internet-based sprinkler status monitoring.

Recent developments have extended basic automatic irrigation through IoT communication and intelligent decision-making. Goap *et al.* [2] proposed an IoT-based irrigation management system that combines field sensor information, weather forecasts, and machine-learning-based soil moisture prediction. Nawandar and Satpute [3] also developed a low-cost intelligent irrigation module with neural-network-based decision support and remote monitoring. These studies indicate that smart irrigation is evolving from simple threshold-based control toward connected systems capable of supporting more informed irrigation decisions.

This paper reviews microcontroller-based smart irrigation systems and their supporting technologies. It focuses on sensing, controller architecture, actuator operation, IoT communication, energy supply, and intelligent irrigation management. The review also identifies practical limitations that should be considered when designing affordable and reliable systems for agricultural applications.

2. MICROCONTROLLER-BASED SMART IRRIGATION ARCHITECTURE

A typical smart irrigation system consists of sensors, a microcontroller, an actuator interface, a water delivery mechanism, and a power supply. Sensors collect information about soil and environmental conditions, while the microcontroller processes the measurements according to the programmed control logic. The actuator interface then operates a pump, valve, or other water distribution device when the irrigation conditions are satisfied.

Arduino-based platforms are frequently used in low-cost prototypes because they provide accessible hardware and programming environments. Rawal [1] described an Arduino Uno implementation using an ATmega328P microcontroller and soil moisture sensors to determine irrigation requirements. The system also communicates sprinkler status to users, illustrating how local automatic control can be combined with remote information access.

The selection of a microcontroller depends on the required number of sensor inputs, communication interfaces, processing capacity, power consumption, and cost. A basic controller may be sufficient for threshold-based irrigation, whereas a more advanced application may require wireless connectivity and additional data processing. The controller should also provide suitable electrical interfaces for sensors and actuators to ensure stable operation. Table 1 summarizes the principal components and their functions in a representative microcontroller-based smart irrigation architecture.

Table 1. Main components of a microcontroller-based smart irrigation system

Component	Main function	Typical implementation
Microcontroller	Processes sensor data and executes control logic	Arduino Uno/ATmega328P
Soil moisture sensor	Measures soil moisture condition	Resistive or capacitive sensor
Temperature and humidity sensor	Monitors environmental conditions	DHT-series sensor
Communication module	Transfers information to remote platforms	Wi-Fi, GSM/GPRS
Actuator driver	Interfaces the controller with electrical loads	Relay or motor driver
Water delivery unit	Supplies water to crops	Pump, solenoid valve, or water gate
Power supply	Provides electrical energy	DC supply, battery, or solar panel

3. SOIL MOISTURE SENSING AND AUTOMATIC IRRIGATION CONTROL

Soil moisture measurement is a central function in automatic irrigation because it provides information about the water condition around plant roots. The sensor converts soil moisture conditions into an electrical signal that can be read by the microcontroller. The controller then compares the measured value with a selected threshold to determine whether irrigation should start or stop.

A threshold-based control method is relatively simple to implement and suitable for small-scale agricultural applications. When the measured soil moisture falls below the predefined lower threshold, the controller activates the pump or opens the irrigation valve. Irrigation can be stopped when the moisture level reaches the required condition, helping prevent unnecessary water application.

However, soil moisture sensors require appropriate installation and calibration. Sensor readings may be influenced by soil type, salinity, temperature, sensor placement, and contact between the sensor and soil. Therefore, a threshold established for one field may not be suitable for another field without additional calibration and testing.

Ismail *et al.* [4] presented an IoT-based irrigation prototype that integrated a soil moisture sensor with temperature, humidity, and pressure sensors. Their system used a NodeMCU-based communication arrangement to upload measurements to cloud platforms for visualization and remote pump control. This example demonstrates how multiple environmental measurements can complement soil moisture data in an automated irrigation application.

4. IOT COMMUNICATION AND REMOTE MONITORING

IoT communication enables irrigation systems to transmit field measurements to remote users and monitoring platforms. This capability allows farmers to observe sensor readings and irrigation status without continuously visiting the field. Depending on the system design, communication can use Wi-Fi, GSM/GPRS,

or other wireless technologies to connect the controller with a web server, cloud service, or mobile application.

Rawal [1] demonstrated the use of GSM/GPRS communication to update sprinkler status on a webpage. Ismail *et al.* [4] used cloud-based services to display sensor measurements and provide remote pump control. These implementations illustrate how communication technology can extend the functionality of a local microcontroller-based controller.

Abba *et al.* [5] developed a low-cost autonomous sensor interface for an IoT-based irrigation monitoring and control system. Their work addressed sensor interfacing and autonomous monitoring and control, with the objective of supporting irrigation operation in remote locations. The study is relevant to system design because reliable sensor interfaces are essential for collecting field data and executing control decisions consistently.

Communication-based monitoring can improve access to irrigation information, but it also introduces additional technical requirements. Network coverage, data transmission reliability, communication delays, and power consumption may affect system performance. A practical design should therefore retain essential local control functions when internet connectivity is unavailable, rather than depending entirely on continuous cloud access.

Bolu *et al.* [6] presented a solar-powered microcontroller-based automated irrigation system using soil moisture sensors. Their prototype determines irrigation requirements from soil moisture conditions and supplies controlled water to the crop root zone. The use of solar energy is particularly relevant to agricultural locations where a reliable grid electricity supply may not be available.

Dokhande *et al.* [7] reviewed an IoT-based smart irrigation implementation using an ATmega328P microcontroller on an Arduino Uno platform, soil moisture sensing, and wireless communication. Their described approach enables sensor information and sprinkler status to be accessed through a mobile application and an online data platform. This demonstrates the potential of combining microcontroller-based control with remote monitoring for agricultural management.

5. ACTUATOR CONTROL AND AUTOMATED WATER DISTRIBUTION

Actuators translate microcontroller decisions into physical irrigation actions. Common devices include water pumps, solenoid valves, and motorized water gates. Because these devices may require more current or voltage than a microcontroller output can provide, an appropriate relay, transistor, or motor driver is necessary between the controller and the actuator.

Automatic pump control is commonly used in small irrigation systems. The microcontroller activates the pump when soil moisture indicates that watering is required and deactivates it when the target condition is reached. Proper electrical protection and suitable switching components are important to reduce the risk of controller damage and unreliable operation.

Microcontrollers can also automate irrigation infrastructure beyond individual pumps and valves. Laumal *et al.* [8] developed an Arduino-based smart irrigation gate for the Manikin Irrigation Area, using a DC motor and a real-time clock to control the opening and closing of the water gate. Their work demonstrates the application of microcontroller technology to scheduled water distribution in an irrigation channel.

The choice of actuator should reflect the physical irrigation infrastructure and the required water flow. Small farms may use compact pumps or solenoid valves, while larger irrigation networks may require motorized gates and more robust control mechanisms. In all cases, the controller should include suitable operating limits and protection measures to prevent actuator malfunction from causing water loss or equipment damage.

6. INTELLIGENT IRRIGATION SCHEDULING AND SYSTEM PERFORMANCE

Basic irrigation systems generally use fixed thresholds, whereas intelligent systems can consider additional information when determining irrigation schedules. Relevant information may include historical soil moisture, weather forecasts, rainfall probability, crop requirements, and environmental measurements. Using these data can help reduce unnecessary irrigation and improve the timing of water delivery.

Goap *et al.* [2] proposed a smart irrigation management system that uses machine learning to predict soil moisture and combines the prediction with weather information for irrigation scheduling. Nawandar and Satpute [3] developed an intelligent irrigation module that uses neural-network-based decision support and supports remote data monitoring through communication protocols. These studies indicate that predictive techniques can extend the capabilities of conventional microcontroller-based irrigation control.

Nevertheless, intelligent scheduling requires suitable data and careful model evaluation. Inaccurate sensor measurements, limited training data, or changes in field conditions may reduce prediction reliability. Therefore, intelligent algorithms should be evaluated under representative agricultural conditions before being used to control irrigation without human supervision. Table 2 compares the main characteristics of the eight reviewed studies, including their principal technologies and contributions to smart irrigation.

Table 2. Comparison of selected smart irrigation studies published up to 2019

Ref.	Authors and year	Main technology or approach	Main contribution
[1]	Rawal, 2017	Arduino, soil moisture sensor, GSM/GPRS	Automatic watering and sprinkler status monitoring
[2]	Goap *et al.*, 2018	IoT, machine learning, weather data	Soil moisture prediction and irrigation scheduling
[3]	Nawandar and Satpute, 2019	IoT, neural network, MQTT/HTTP	Low-cost intelligent irrigation and remote monitoring
[4]	Ismail *et al*., 2019	NodeMCU, multiple sensors, cloud	Environmental monitoring and remote pump control
[5]	Abba *et al.*, 2019	Autonomous sensor interface, IoT	Low-cost irrigation monitoring and control interface
[6]	Bolu e*t al.*, 2019	Microcontroller, moisture sensors, solar power	Automated irrigation using renewable energy
[8]	Laumal *et al*., 2017	Arduino, real-time clock, DC motor	Automated irrigation water gate
[7]	Dokhande *et al*., 2019	Arduino, soil moisture sensor, Wi-Fi	IoT-based irrigation monitoring through an application

The studies in Table 2 demonstrate that smart irrigation systems can be developed with different levels of complexity. Low-cost microcontroller platforms provide a practical foundation for sensing and automatic control, while IoT communication enables remote monitoring and intelligent methods support more advanced scheduling. The most appropriate configuration depends on field size, crop requirements, available infrastructure, and the resources of the intended users.

7. CHALLENGES AND FUTURE DEVELOPMENT

Despite their potential, smart irrigation systems face several implementation challenges. Sensor accuracy and durability are important because agricultural sensors operate in environments exposed to moisture, soil particles, temperature changes, and possible corrosion. Regular calibration and maintenance are therefore necessary to maintain reliable measurements over time.

Communication and energy availability also influence the suitability of an irrigation system. Remote agricultural areas may have limited internet coverage or unstable electricity supplies, making low-power communication and renewable energy options valuable. Local control should remain operational during communication interruptions so that irrigation does not depend entirely on remote services.

Future systems can improve irrigation decisions by combining soil moisture measurements with weather forecasts, crop-specific requirements, and historical field data. More robust designs may also include fault detection, data logging, manual override, and protective mechanisms for pumps and valves. These features can improve reliability and make smart irrigation systems more practical for long-term agricultural use.

8. CONCLUSION

Microcontroller-based smart irrigation systems provide a practical method for automating water delivery according to measured field conditions. The reviewed studies show that platforms such as Arduino and other embedded controllers can integrate soil moisture sensors, actuators, communication modules, and renewable energy sources. IoT connectivity further enables remote monitoring, while machine-learning methods offer opportunities for predictive irrigation scheduling. However, successful implementation requires more than connecting sensors and actuators to a microcontroller. Sensor calibration, reliable power, communication availability, appropriate actuator interfaces, and field testing must all be considered during system development. A robust smart irrigation system should combine dependable local automation with remote monitoring and suitable decision-making methods to support efficient agricultural water management.

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