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AI-driven and sensor-based real-time irrigation and water management: A Review

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Abstract

This review systematically examines recent advancements in AI-driven irrigation systems and their role in achieving sustainable water management under climate-resilient agricultural practices. By integrating machine learning algorithms, computer vision, and IoT-based sensors, these autonomous systems enable real-time soil–plant monitoring, adaptive water scheduling, and resource optimization across diverse agro-climatic contexts. Drawing upon a broad range of peer-reviewed experimental and modeling studies published between 2018 and 2025, the review highlights measurable improvements in water-use efficiency, energy savings, and crop productivity. Meta-analytical synthesis using random-effects models was employed to quantify water savings (30–50 %) and yield improvements (20–30 %), while subgroup analyses compared algorithmic performance (e. g., Random Forest, SVM, CNN) and irrigation methods. Moreover, the study discusses economic feasibility, system interoperability, sensor calibration protocols, and ethical considerations related to data governance. Findings reveal that AI-enabled irrigation offers scalable and cost-effective solutions for climate adaptation, especially in drought-prone and infrastructure-limited regions. Future research opportunities include standardization frameworks, cross-platform compatibility, and expanding validation across diverse crop types and regional settings. Eventually, this paper is keen on offering comprehensive background information about sensor-based irrigation systems and their undeniable ability to upgrade agricultural water management, preserve water resources, and be incorporated in food security issues for the sake of changing climate change.

Keywords: AI-enhanced irrigation, smart agriculture, IoT-based monitoring, machine learning, climate resilience, precision farming

1. Introduction:

Due to the rising demands for increased food production and extreme water scarcity and climate change, there is a need for developing an efficient irrigation system for supplying water to crop lands. It is agriculture that is the largest consumer of water resources, as it accounts for nearly 70% of global freshwater withdrawals (FAO, 2021). However, traditional irrigation methods like flood irrigation and fixed scheduling result in wastage of water, degradation of soil, and less productive crops caused by imperfect distribution and evaporative losses. In addition, the uncertainty of the conditions of climate increases the probability of over- and under-irrigation, which contributes to worse health of the crop and reduction of the total yield. To deal with these situations, smart irrigation systems have been devised as a sustainable solution that uses technologies like artificial intelligence (AI), machine learning (ML), and environmental monitoring. In this regard, intelligent systems work in accordance with dynamically adjusted irrigation schedules by sensing the real-time environmental conditions, thereby enhancing the water efficiency and the reduction of the need for manual intervention. Many smart irrigation systems use Internet of Things (IoT) technologies to acquire real-time data and to control the system remotely, but the implementation of such IoT-based infrastructure is expensive and complicated, and also it highly depends on the network connectivity.

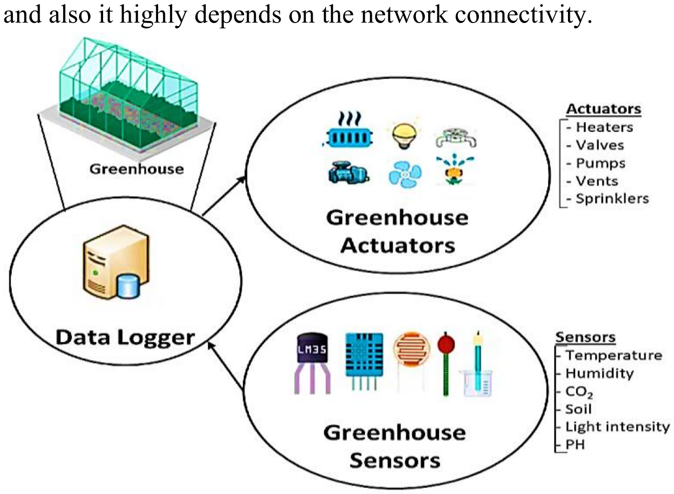


Figure 1: Smart Sensors and Smart Data for Precision Agriculture. ***Sensors* 2024, *2647; https://doi.org/10.3390/s24082647***

In rural and remote areas where connectivity is scarce, IoT solutions cannot be viable, resulting in a need for non-IoT-based solutions that can act autonomously without constant connectivity. The aim of this research is to build a non-IoT-based smart irrigation system integrating the AI-driven predictive modeling and the adaptive algorithms to optimize the water distribution in precision agriculture. The system uses machine learning techniques to study historical as well as real-time data of soil moisture, crop water requirements, and forecasted weather to make precise decisions of irrigation. This approach is unique when compared to the conventional irrigation models, where the water is wasted due to improper irrigation of crops and cycles which can only be managed by anticipating the environmental conditions which are not in their control otherwise, crops are improper irrigated and are left under watered or over watered. This system's core is Adaptive Smart Irrigation Model, which integrates the decision-making algorithm that considers the soil moisture levels, weather

Fig 2: Precision Agriculture: Transforming Farming with AI and Data-Driven Insights. ***Source: https://etedge-insights.com/industry/agriculture/ai-is-transforming-agriculture-in-india-by-providing-cutting-edge-solutions-for-farmers/***

conditions and crop specific water requirements to regulate the cycle of irrigation. The system does away with the need for constant human monitoring, also improving over time in a feedback loop and becomes better with each cycle. Evaluations based on a simulation technique are carried out for the assessment of the effectiveness of the system in terms of such parameters as water conservation, crop yield, and the efficiency of resource utilization. Experimental studies result reveal that this AI powered, non IoT based smart irrigation system considerably improves water use efficiency and agricultural productivity and serves as an eco-friendly solution for farmers in general and especially in areas where traditional IoT infrastructure is infeasible. Due to ongoing climate change imposing water unavailability at global level, incorporating AI in irrigation system has emerged as a scalable, cost effective and sustainable solution to solve water management and food security issues.

AI-driven and sensor-based real-time irrigation systems revolutionize water management by integrating IoT sensors *(soil moisture, temperature, climate) with machine learning algorithms to automate water delivery, cutting usage by 30–50% and boosting yields by 20–30%. These systems optimize precision, reduce labor, and adapt to climate variability.*

Key Aspects of AI-Driven & Sensor-Based Irrigation

Real-time Monitoring & Data Acquisition: *Sensors continuously monitor environmental parameters, including soil moisture, temperature, humidity, and weather data, allowing for immediate adjustments to irrigation scheduling.*

AI and Machine Learning (ML) Integration: *Algorithms like Random Forest, Support Vector Machines (SVM), and Convolutional Neural Networks (CNN) process sensor data to predict the best irrigation schedules. These systems can even utilize computer vision to monitor crop health and analyze video streams for field conditions.*

Automation and Control: *The system, often utilizing microcontrollers like Arduino, automatically controls pumps and valves based on AI decisions, removing the need for manual intervention.*

Key Benefits:

Water Conservation: *Significant reduction in water usage (30-50% reported).*

Improved Crop Yields: *Optimal water application leads to better growth and increased yields (20-30% improvements).*

Operational Efficiency: *Reduced labor costs and improved, data-driven decision-making.*

Sustainability: *Enhanced resilience to drought and reduced water wastage through precise, tailored irrigation.*

Challenges and Future Directions: *While beneficial, these systems face challenges in sensor calibration and require continued development to improve decision-making accuracy. Future trends include greater integration of satellite data for, and increased affordability of these technologies.*

1.1. Objective and Scope of the Review Objectives:

- To evaluate and summarize the advancements in IoT and AI technologies applied to smart irrigation systems across various agricultural settings.
- To analyze the performance, benefits, and limitations of machine learning models and IoT architectures in precision irrigation.
- To identify the technological gaps, deployment challenges, and future directions for intelligent irrigation solutions tailored to diverse climatic and socio-economic conditions.

1.2. Scope of the Review: This review encompasses interdisciplinary studies concentrating on how agricultural irrigation systems incorporate AI and the Internet of Things. It includes research from the domains of agronomy, computer science, sensor technology, and data analytics that address automation, water-use efficiency, and crop specific irrigation strategies. Emphasis is placed on machine learning techniques for predictive modeling and IoT infrastructures for real-time data acquisition and control. The review spans both conceptual frameworks and practical implementations published over the past twenty years, with special attention to systems designed for developing and water-stressed regions. It investigates technological challenges such as sensor calibration, energy constraints, communication protocols, and data handling. Additionally, it outlines emerging innovations like deep learning, edge computing, and smart decision support systems, presenting opportunities for scalable, sustainable, and cost-effective irrigation management solutions.

2. System Architecture of IoT-Based Smart Irrigation: An IoT-based smart irrigation system is generally designed

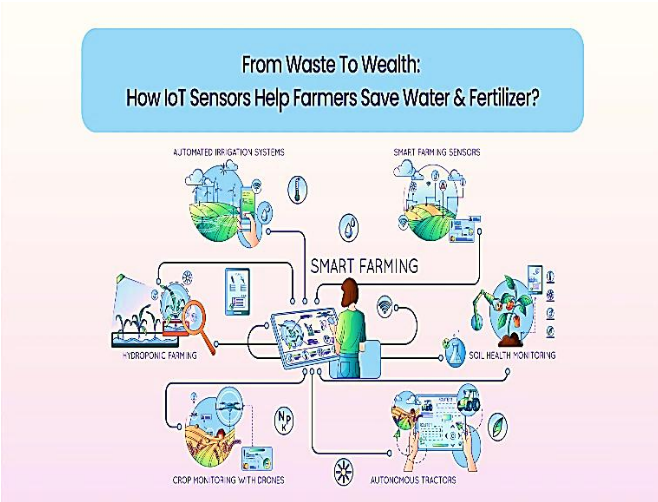


Fig 3: Sketch out the Smart Sensor technology.

with a four-layer architecture, where each layer performs a specific function to ensure efficient and automated water management. The layers are described below:

1. Sensing Layer: This layer is responsible for collecting real-time data from various sensors installed in the agricultural field. These sensors measure key environmental parameters such as soil moisture, temperature, humidity, and rainfall, which are essential for determining irrigation needs.

2. Processing and Connectivity Layer: The data gathered by the sensors is sent to a microcontroller or processing unit, such as an Arduino or ESP32. Here, the data is processed and transmitted to a cloud platform using wireless communication technologies like Wi-Fi, GSM, or LoRa. This layer acts as the bridge between field-level data collection and remote decision-making.

3. Actuation and Control Layer: Based on the processed data and programmed logic, this layer executes irrigation commands. It controls components such as pumps and solenoid valves, turning them on or off to deliver the required amount of water. This automation reduces human effort and ensures precise water distribution.

4. Application Layer: The final layer provides a user interface, accessible through a mobile application or web dashboard. Farmers can monitor field conditions, view Realtime data, receive alerts, and manually control irrigation when needed. This layer enables remote monitoring and management, making the system user-friendly and efficient.

2.1 Sensing Layer (Data Acquisition Layer): The sensing layer serves as the foundation of an IoT-based smart irrigation system. It is responsible for monitoring key field parameters and converting physical quantities—such as soil moisture, temperature, and light intensity—into digital signals that can be processed by the system. This layer ensures that all decisions are based on real-time, accurate field data rather than manual estimation. The main sensors used in this layer include.

2.1.1. Soil Moisture Sensor: This is the most important sensor in any irrigation system. It measures the volumetric water content in the soil, helping determine when plants actually need water. Common types include capacitive and resistive sensors. When soil moisture drops below a predefined threshold, the sensor sends a signal to the controller to start irrigation, ensuring optimal soil moisture levels.

2.1.2. Temperature and Humidity Sensor (DHT11/DHT22): These sensors monitor ambient temperature and humidity. Temperature affects the rate of evaporation, while humidity influences plant transpiration. By tracking both, the system can decide the best timing and duration for irrigation, reducing water waste and improving crop health.

- **Rain Sensor:** This sensor detects rainfall and prevents unnecessary watering during or after natural precipitation. It helps conserve water and protects plants from over-irrigation.
- **Light Sensor (LDR – Light Dependent Resistor):** The light sensor measures sunlight intensity, which is useful in solar-powered irrigation systems to optimize energy consumption. It can also help in understanding plant photosynthesis patterns and adjusting irrigation schedules accordingly.
- **Water Level Sensor:** This sensor monitors the water level in storage tanks or reservoirs, ensuring that there is sufficient water available for irrigation. If the level is low, the system can alert the user or automatically stop the pump to prevent damage.
- **Working Principle:** All sensors generate analog or digital signals representing real-time field conditions. These signals are then sent to the microcontroller, which processes the data and decides whether irrigation is required.

2.2 Processing and Connectivity Layer

The Processing and Connectivity Layer serves as the "brain" of an IoT-based smart irrigation system. It is responsible for analyzing sensor data, making irrigation decisions, and ensuring communication between field devices and cloud platforms. This layer bridges the gap between raw sensor readings and meaningful, automated irrigation actions.

3. Main Components:

3.1. Microcontroller (ESP32, Arduino, or Raspberry Pi): The microcontroller is the central control unit that reads sensor data, processes information, and operates actuators such as relays and solenoid valves. Among these, the ESP32 is widely used because it has built-in Wi-Fi and Bluetooth connectivity.

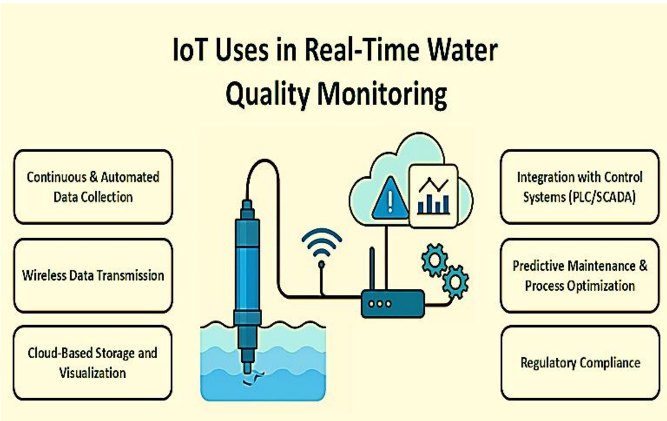


Figure 4: IoT Used in Real-time Water Quality Monitoring. Source: https://www.rikasensor.com/blog/why-is-iot-used-in-real-time-water-quality-monitoring.html

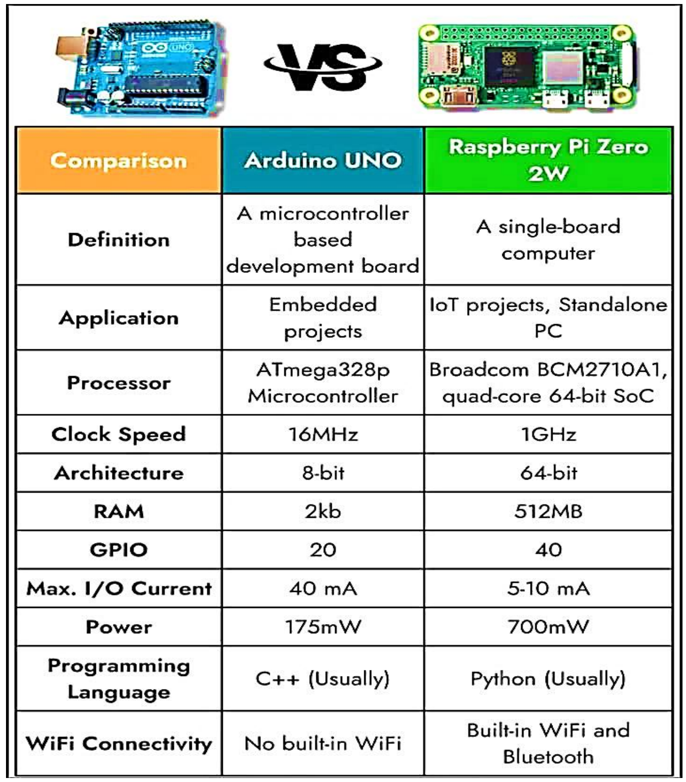
making it ideal for IoT applications. It executes programmed logic to determine when irrigation should start or stop, based on real-time field conditions.

3.2. Communication Modules: These modules enable data transfer between the microcontroller and remote systems (such as the cloud or mobile app). The choice of communication technology depends on farm location and connectivity needs:

Wi-Fi: Suitable for areas close to routers or local networks where stable internet access is available

GSM/GPRS: Uses SIM card-based mobile networks, ideal for rural regions without fixed internet connections. LoRa (Long Range): Provides long-distance, low-power communication, making it effective for large or remote farms. ZigBee/Bluetooth: Best suited for short-range communication between nearby sensors and devices. Edge Processing: Some advanced systems use edge computing, where data is processed locally on the device rather than sending it to the cloud. This allows the system to make quick decisions even when internet connectivity is poor or unavailable. It also reduces data transmission costs and improves reliability by ensuring uninterrupted irrigation control.

3.3 Actuation and Control Layer: The Actuation and Control Layer is responsible for executing the commands received from the processing unit. It translates digital decisions into physical actions, such as turning on a pump or opening a valve to start irrigation. This layer forms the hands of the system, ensuring that automated responses are accurately carried out in the field. Key Components: Relay Module: The relay acts as an electrical switch that controls the operation of devices such as water pumps or solenoid valves. It allows the microcontroller to manage high-power electrical equipment safely and efficiently. Solenoid Valves: These valves regulate the flow of water to different sections of the field. When activated, they open to allow water passage, and when deactivated, they close to stop the flow. This enables precise water distribution based on crop requirements. Pump Motor: The pump motor draws water from the source—such as a tank, well, or reservoir—and supplies it to the irrigation lines. It operates automatically based on control signals received from the relay module. Power Supply: The entire system requires a stable power source, which can come from electricity, batteries, or solar panels. Solar energy is often preferred for remote agricultural fields, as it supports sustainable and off-grid operation.



Comparison	Arduino UNO	Raspberry Pi Zero 2W
Definition	A microcontroller based development board	A single-board computer
Application	Embedded projects	IoT projects, Standalone PC
Processor	ATmega328p Microcontroller	Broadcom BCM2710A1, quad-core 64-bit SoC
Clock Speed	16MHz	1GHz
Architecture	8-bit	64-bit
RAM	2kb	512MB
GPIO	20	40
Max. I/O Current	40 mA	5-10 mA
Power	175mW	700mW
Programming Language	C++ (Usually)	Python (Usually)
WiFi Connectivity	No built-in WiFi	Built-in WiFi and Bluetooth

Figure 5: Arduino UNO is a simple microcontroller board ideal for embedded and control-based projects, using an 8-bit ATmega328p processor with limited memory and no built-in Wi-Fi.

3.4 Application Layer (Cloud and User Interface)

The application layer serves as the connection between the farmer and the irrigation system, enabling real-time interaction and control through the internet. It allows users to access field data, monitor conditions, and manage irrigation remotely from anywhere at any time. Main Functions: Data Storage and Visualization: Field data collected from sensors is uploaded to cloud platforms such as Blink, Thing Speak, or Firebase, where it is securely stored and visualized in the form of charts and dashboards. This helps farmers easily interpret trends in soil moisture, temperature, and humidity over time. Mobile and Web Applications: User-friendly mobile and web apps allow farmers to monitor and control their irrigation systems remotely. Through these interfaces, users can start or stop irrigation, view live data, and receive system updates without being physically present in the field. Real-Time Alerts and Notifications: The system can send instant alerts via SMS, email, or app notifications whenever critical conditions occur—such as low soil moisture, pump failure, or connectivity issues. These alerts help farmers respond quickly to prevent crop stress or equipment damage. Data Analysis and Historical Trends: Cloud platforms also maintain historical records of environmental data, allowing farmers to analyze past irrigation patterns. This information supports better decision-making for future water management and crop planning.

4. Working Principle: The IoT-based smart irrigation system operates on a closed-loop control process, where continuous monitoring and automated actions ensure that crops receive the right amount of water at the right time. The entire process can be explained in the following steps:

1. Data Monitoring: Sensors installed in the field continuously measure soil and environmental parameters such as soil moisture, temperature, and humidity. These readings reflect the real-time condition of the field.

2. Data Processing and Comparison: The microcontroller collects the sensor data and compares it with present threshold values. For example, if the soil moisture level falls below the required limit, the system recognizes that the soil is dry.

3. Automatic Pump Activation: When dryness is detected, the relay module sends a signal to activate the water pump. This allows water to flow through pipes or drip irrigation lines to the root zone of the crops.

4. Irrigation Control: The system continues watering until the desired soil moisture level is reached. Once the soil moisture sensor detects that the threshold has been achieved, the microcontroller automatically turns off the pump, preventing over-irrigation. 5. Data Logging and Cloud Storage: Throughout the process, all readings—such as soil moisture, temperature, humidity, and water usage—are uploaded to the cloud. This allows the data to be stored, analyzed, and accessed remotely by the farmer through a mobile or web interface.

4. Benefits and Advantages IoT-based smart irrigation systems bring multiple benefits to modern agriculture, improving both productivity and sustainability. The major advantages are discussed below: 4.1 Water Conservation One of the most significant benefits of smart irrigation is efficient water use. By continuously monitoring soil moisture, temperature, and humidity, the system ensures that water is supplied only when the soil is dry and in the exact amount required. This approach can reduce water wastage by up to 50% compared to traditional irrigation. For instance, in a drip irrigation setup, soil moisture sensors prevent unnecessary watering, helping to conserve valuable freshwater resources and reduce groundwater depletion.

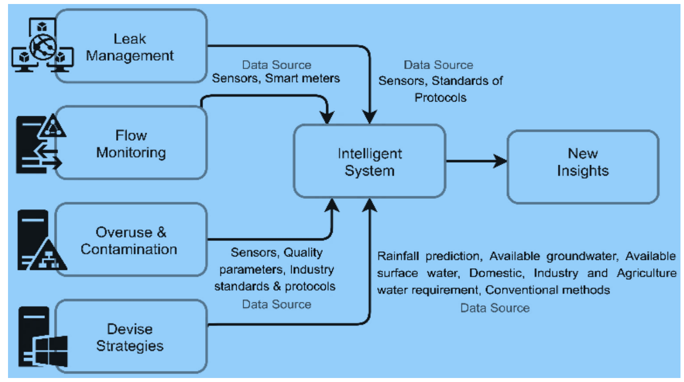


Fig 6: Harnessing intelligent systems for water management.

4.2 Increased Crop Yield: Crops grow best when they receive the right amount of water at the right time. IoT systems help maintain optimal soil moisture conditions, which improves root development, nutrient absorption, and overall plant health. Studies have shown that using smart irrigation can increase the yield of crops such as wheat, maize, and vegetables by 15–30%, leading to better productivity and food quality.

Figure7: Intelligent plant diagnostic systems: opportunity or risk for the gardener? Source: https://ogrodnik.ai/inteligentne-systemy-diagnostyki-roslin

4.3 Reduced Labor and Cost Traditional irrigation requires regular human supervision to open and close valves, monitor field conditions, and manage water distribution. Smart irrigation systems automate these tasks, saving farmers time, effort, and labor costs. This automation also helps in reducing human error, making the system more reliable and cost-effective in the long run. 4.4 Energy Efficiency IoT systems help save energy by operating pumps only when necessary. Since the motor or pump runs for shorter and more efficient cycles, electricity consumption is reduced. In some cases, solar-powered irrigation systems are used, making the system even more sustainable and suitable for remote areas without stable power supply.

4.5 Remote Monitoring and Control Farmers no longer need to be physically present in the field to manage irrigation. Through mobile or web applications, they can monitor soil conditions, control water flow, and receive alerts about low moisture levels or system faults. This remote accessibility improves convenience and enables quick decision-making, especially for large farms or multiple field locations. 4.6

Environmental Protection Smart irrigation promotes eco-friendly farming by preventing overwatering and reducing water runoff. Controlled irrigation helps minimize soil erosion, salinity, and nutrient leaching, thereby maintaining soil health and fertility. Efficient water use also contributes to sustainable groundwater management and supports long-term agricultural productivity.

4.6. Data Analytics for Better Decision-Making The continuous collection of field data provides valuable insights into soil behavior, crop water needs, and environmental trends. By analyzing historical data, farmers can predict irrigation requirements, plan cropping patterns, and optimize fertilizer and water use. This data-driven approach transforms farming into a more scientific and informed process, improving both efficiencies.

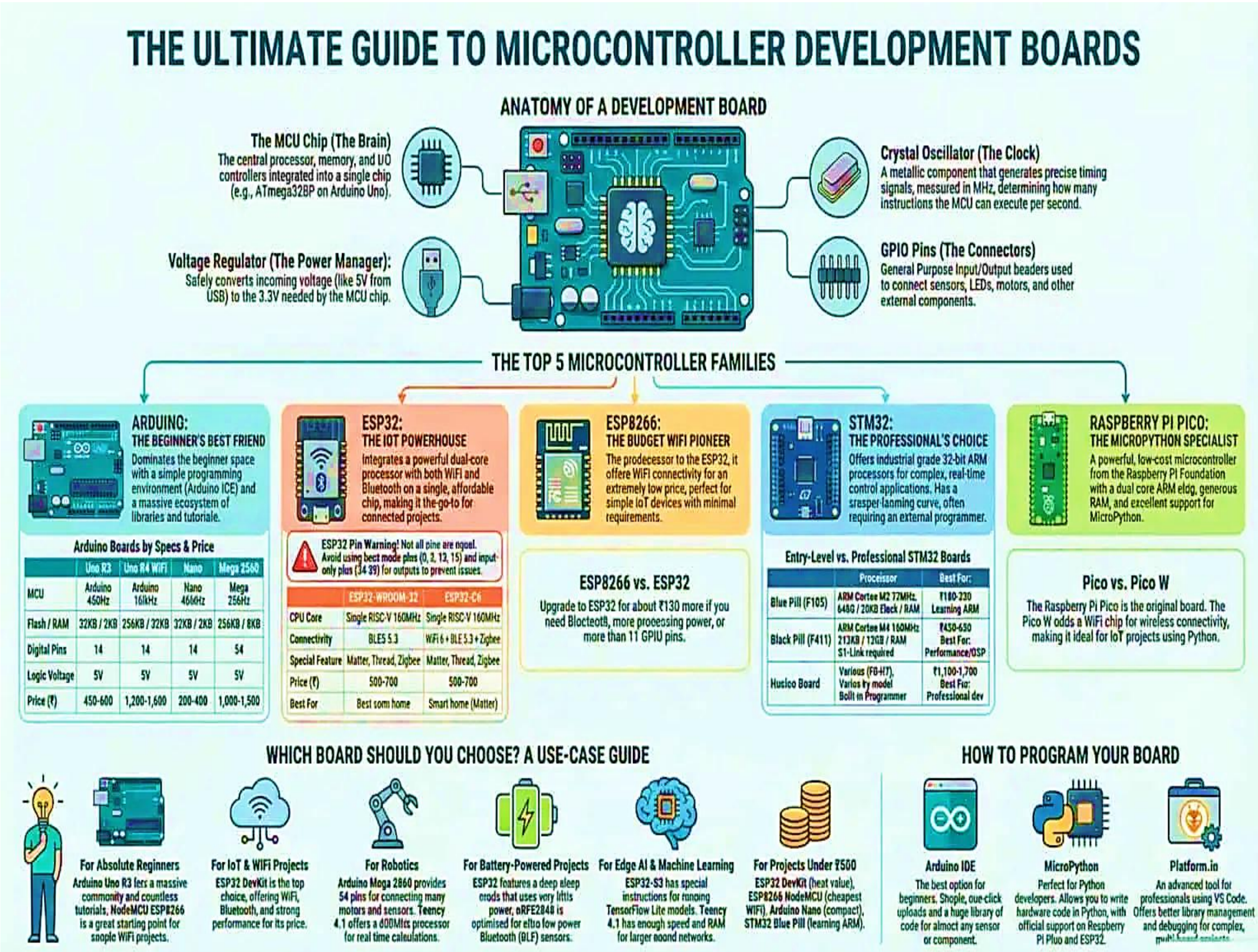


Fig 8: Complete Microcontroller Boards Infographic. ***Sources: earniot.in/microcontroller-development-boards-guide/***

5. System Analysis

A. Functional requirement Collect real-time data from soil moisture, temperature, and humidity sensors. Automatically control water pumps based on sensor readings. Store and visualize data through Power BI dashboards. Provide remote monitoring and multilingual user access. Send alerts when soil moisture is too low or high.

B. Non-Functional Requirement System must be reliable, secure, and scalable. Real-time data updates with minimal delay. Easy to use for farmers with simple interface design. Accurate sensor readings and low maintenance.

C. Hardware Requirement

1) Raspberry Pi (Controller)
2) Soil Moisture, DHT11 Sensors
3) Relay Module and Water Pump
4) Power Supply, Wi-Fi Module
5) Jumper Wires, Breadboard

D. Software Requirement

1) Raspberry Pi OS, Python
2) Power BI for Data Visualization
3) Cloud Platform (Thing Speak / Firebase)
4) HTML, CSS, JavaScript for Web Dashboard
5) SQL/NoSQL Database

E. Module Description

1) Sensor Module: Collects real-time soil moisture, temperature, and humidity data using IoT sensors.

2) Processing & Control Module: Raspberry Pi/ESP32 processes sensor data and automatically controls the water pump through a relay.

3) Cloud & Database Module: Stores sensor data on cloud platforms like Thing Speak or Firebase for analysis and remote access.

4) Dashboard & Visualization Module: Displays live sensor readings and irrigation status using Power BI dashboards for easy monitoring.

5) User Interface Module: Allows farmers to monitor and control irrigation via a multilingual web or mobile app. 6) Communication Module: Handles data transfer between sensors, the controller, and the cloud using Wi-Fi or GSM.

7) Alert & Notification Module: Sends alerts to farmers when soil moisture is low or system faults occur.

8) Data Analytics Module: Analyzes stored data to optimize water usage and predict irrigation needs.

6. Future Enhancement

1) AI-Based Prediction: Integrate machine learning models to predict optimal irrigation schedules based on soil type, crop growth stage, and weather conditions.

2) Weather Forecast Integration: Connect the system with real-time weather APIs to automatically adjust irrigation during rainfall or high humidity periods.

3) Fertilizer Automation: Extend the system to control fertilizer mixing and distribution using IoT-enabled nutrient sensors.

4) Mobile Application Development: Create a dedicated mobile app for farmers to monitor live data, control irrigation remotely, and receive instant alerts.

5) Voice Command Control: Implement voice assistant features in local languages for easy use by farmers with limited technical knowledge.

6) Solar Energy Integration: Use solar panels to power sensors and pumps, reducing dependency on electricity and promoting renewable energy use.

7) Drone-Based Field Monitoring: Add drone technology to capture aerial images, assess crop health, and detect irrigation coverage.

8) Blockchain for Data Security: Employ blockchain technology to securely record sensor data and ensure data transparency and reliability.

9) Advanced Analytics Dashboard: Enhance Power BI or cloud dashboards with predictive insights, charts, and historical trend analysis. Scalability for Large Farms: Expand the system to manage multiple irrigation zones and large-scale a

7. Future Directions and Innovations: The future of IoT-based smart irrigation systems looks promising, with ongoing advancements in sensor technology, wireless communication, and machine learning. Some potential future developments include:

1. Integration with Artificial Intelligence (AI): AI and machine learning algorithms can analyze the data collected by IoT systems to predict irrigation needs more accurately, improve crop management practices, and automate decision-making processes.

2. Solar-Powered Systems: Combining IoT irrigation systems with solar energy can provide a sustainable and cost-effective solution for remote areas without reliable electricity access.

3. Integration with Weather Forecasting: IoT systems could be further integrated with weather forecasting services to adjust irrigation schedules based on real-time weather predictions, optimizing water usage and reducing wastage.

4. Water Quality Monitoring: IoT-based irrigation systems can be expanded to include sensors for monitoring water quality, ensuring that irrigation water is free from contaminants and safe for crops.

7. Integration with Artificial Intelligence (AI) Artificial intelligence can analyze vast amounts of field data to predict irrigation needs and determine the optimal amount of water for crops. For example, AI algorithms can combine soil moisture readings with weather forecasts to create dynamic, adaptive irrigation schedules, ensuring that crops receive water precisely when needed. 6.2 Machine Learning (ML) Models Machine learning techniques, such as LSTM (Long Short-Term Memory) networks and Random Forest algorithms, can forecast soil moisture trends and automatically optimize irrigation intervals. These predictive models reduce water waste, improve crop health, and make irrigation more data-driven and precise.

7.1. Edge and Cloud Computing By combining edge computing (local processing on the device) with cloud computing (remote processing), smart irrigation systems can make faster and more reliable decisions, even in areas with unstable or limited internet connectivity. This hybrid approach ensures continuous automation and reduces reliance on external networks.

7.2. Blockchain Technology: Blockchain technology can provide secure and transparent management of agricultural data. For large-scale farms and cooperative systems, blockchain ensures that sensor data, water usage records, and irrigation schedules are immutable and easily auditable, enhancing trust and accountability.

8. Challenges and Limitations

Despite the numerous benefits, IoT-based smart irrigation systems face several challenges and limitations that can affect their adoption and effectiveness, especially for small-scale farmers. 5.1 High Initial Investment The cost of installing a smart irrigation system can be significant. Components such as sensors, microcontrollers, communication modules, and actuators contribute to the high initial expense. This investment can be a major barrier for small and marginal farmers, limiting widespread adoption. 5.2 Maintenance Requirements Sensors and other electronic components are often exposed to soil, water, and varying weather conditions, which makes them prone to wear and malfunction. Regular cleaning, calibration, and occasional replacement are required to maintain accurate measurements and reliable operation.

8.1. Connectivity Issues Real-time monitoring and automated control depend on stable internet or GSM connectivity. However, many rural areas suffer from weak or unreliable network coverage, which can disrupt system performance and delay irrigation decisions. 5.4 Technical Skills Farmers need basic technical knowledge to operate, configure, and troubleshoot smart irrigation systems. Without proper training, they may struggle to manage the system effectively, which can reduce its efficiency and benefits. 5.5 Standardization Challenges The wide variety of sensor types, communication protocols, and IoT platforms can create compatibility issues. Integrating devices from different manufacturers may be difficult, requiring careful planning and configuration to ensure smooth operation

8.2. Renewable Energy Integration Integrating solar panels or other renewable energy sources enables smart irrigation systems to operate off-grid, reducing dependence on conventional electricity. This makes the technology more sustainable and suitable for remote or rural areas. 6.6 Smart Fertigation Future smart irrigation systems are expected to go beyond water management by incorporating fertigation—the controlled delivery of nutrients along with water. This approach ensures that crops receive the right balance of water and nutrients, maintaining optimal soil conditions for maximum growth and productivity. 6.7 Government and Research Support Support from government programs, research institutions, and open-source initiatives can make smart irrigation more accessible and affordable. Subsidies, technical training, and university collaborations can help farmers adopt advanced technologies, accelerating the shift toward precision and sustainable agriculture.

8.3. Why, Need for Smart Irrigation Systems

Smart irrigation systems offer cutting-edge technology to assist growers in monitoring and maximizing yield. These systems can be seamlessly integrated into existing irrigation setups. By tracking, automating, and analyzing water usage, smart irrigation systems enable users to identify leaks, minimize waste, and receive prompt alerts regarding potential issues.

Given the impact of climate change on water availability and the growing global population, the adoption of smart water technology has become increasingly crucial. Smart irrigation not only reduces water consumption but also decreases reliance on manual labour, enhances landscape health, and reduces costs.

8.3. Role of AI in Smart Irrigation Systems

1. Predict water and fertilizer requirements

AI algorithms analyze live data from weather sensors, radars, and stations. This real-time analysis enables AI to produce timely forecasts, aiding growers and decision-makers to plan and take proactive measures to ensure consistent water supply and suitable soil conditions.

AI/ML models can aid growers in scheduling activities like planting and harvesting according to expected weather conditions. This predictive approach enhances system efficiency and optimizes water usage. Additionally, AI models forecast water availability, enabling farmers to efficiently manage irrigation schedules and prevent under- or over-watering. Anticipating rainfall and other climatic variations helps farmers prepare for natural challenges.

2. Monitor Crop Health

AI-driven smart irrigation systems utilize computer vision to monitor plants through on-field sensors and satellite imaging. These devices track crucial parameters such as plant stress and leaf wetness, while plant sensors detect early signs of diseases, pest infestations, or nutrient deficiencies. This enables targeted interventions to protect crop health and minimize reliance on chemical treatments.

3. Data-driven Decision Making and Precision Farming

The integration of AI technology and sensors in smart agriculture facilitates precision farming. AI algorithms analyze insights from various sensors (weather, soil, and plant), drones, and satellite imaging to optimize irrigation, pest control, and fertilizer application. By monitoring parameters like temperature, soil moisture, and nutrient content, this technology empowers farmers to make informed, data-driven decisions, ensuring efficient resource utilization.

4. Remote Monitoring and Control

AI-based automated irrigation systems offer remote control and monitoring through mobile apps or web interfaces. This allows landscapers and property owners to manage irrigation processes, receive alerts, and adjust settings from any location, providing convenience and flexibility while reducing manual intervention.

8.4. Key Benefits

1. Sustainable Use of Water

Harnessing the power of advanced algorithms, AI-driven smart irrigation systems can greatly support water conservation in agriculture. These innovative systems ensure efficient water usage while championing environmental sustainability by continuously monitoring soil moisture levels, weather patterns, and plant requirements. By preventing over-irrigation and runoff, AI-based solutions can play a pivotal role in combating global water scarcity, offering a compelling reason to embrace this transformative technology.

2. Preserve soil health

Soil moisture plays a crucial role in regulating the moisture in a plant. In the long term, irrigation practices can positively or negatively impact the health of soil. Unsuitable irrigation practices may result in the buildup of salts and chemicals in soil and water, a phenomenon commonly referred to as salinization or waterlogging. Soil that is either excessively dry or overly saturated can impose stress on plants, making them susceptible to diseases and compromising future harvests. Hence, AI monitoring and prediction of soil moisture levels is imperative to strategically schedule irrigation, ensuring crops receive the precise amount of water needed for optimal growth and maximum yields.

3. Enhanced Crop Yield

With AI at the helm, growers can unlock the full potential of their crops by providing tailored irrigation schedules based on intricate factors such as crop varieties, soil conditions, and dynamic environmental changes. This data-driven approach helps protect crops from pests and diseases and significantly boost crop yields, presenting a compelling argument for integrating AI into agricultural practices.

4. Economies of Scale

The adoption of AI-based smart irrigation systems presents a compelling business case for large-scale growers. By automating irrigation operations and minimizing the need for manual labor, these systems drive down long-term operational costs while maximizing efficiency. Furthermore, the reduction in water wastage and fertilizer usage translates into tangible economic benefits, making AI an ally for large-scale seed and food manufacturing firms seeking to optimize their operations.

9. Conclusion

The Smart Irrigation System for Precision Farming successfully demonstrates how IoT and automation can revolutionize traditional agricultural practices. By integrating soil moisture, temperature, and humidity sensors with microcontrollers and cloud platforms, the system enables real-time monitoring and automatic irrigation based on crop and soil conditions. This not only reduces human effort but also ensures optimal water usage, leading to increased crop yield and sustainability. The system's dashboard allows farmers to view real-time data, control irrigation remotely, and receive instant alerts. Overall, the project achieves its objective of promoting efficient resource utilization and supports the vision of smart and sustainable agriculture. The implementation of this Smart Irrigation System proves that automation and IoT can play a vital role in solving agricultural challenges. It helps farmers make data-driven decisions rather than relying on manual observation. The system's ability to automatically control irrigation reduces water wastage and ensures crops get the right amount of moisture at the right time. This project highlights how technology can empower farmers to increase efficiency, save resources, and move toward sustainable farming practices.

The IoT-based Smart Irrigation System marks a transformative step toward achieving sustainable, efficient, and technology-driven agriculture. By integrating advanced sensors, microcontrollers, and cloud-based data analytics, these systems allow farmers to monitor soil moisture, temperature, and humidity in real time. This data-driven approach enables precise water delivery—supplying the right amount of water at the right time—thereby minimizing waste and ensuring optimal plant growth. Such automation not only enhances crop productivity but also significantly reduces manual labor, water consumption, and operational costs, contributing to both economic and environmental benefits. As the world faces challenges like climate change, unpredictable rainfall, and water scarcity, smart irrigation emerges as a powerful solution to balance agricultural needs with ecological sustainability. However, the widespread adoption of these systems still faces challenges, including high installation costs, technical complexity, and limited internet connectivity in rural areas. Despite these barriers, rapid advancements in Artificial Intelligence (AI), Machine Learning (ML), renewable energy integration, and low-cost IoT components are steadily overcoming these limitations. Looking ahead, the convergence of IoT with emerging technologies such as drones, blockchain, and predictive weather analytics will further revolutionize modern farming practices. These innovations will empower farmers with greater control, accuracy, and sustainability in water management. Ultimately, the adoption of IoT-based smart irrigation systems signifies a paradigm shift toward precision agriculture, where every resource is optimized for maximum output with minimal environmental impact. With continued research, strong policy support, and increased awareness among farmers, this technology has the potential to ensure global food security, climate resilience, and a greener agricultural future.

10. Ethics declarations

10. 1. Ethics approval and consent to participate

Not applicable.

10.2. Consent for publication

Not applicable.

10.3. Competing interests

The authors declare that they have no competing interests.

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The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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20. Background: The integration of Artificial Intelligence (AI) in agricultural practices has witnessed substantial advancements, with a focus on enhancing efficiency and sustainability. This research explores the application of AI-powered robotic harvesting systems for legume crops, aiming to revolutionize traditional harvesting methods. By leveraging machine learning algorithms and robotic technology, this study investigates the feasibility and performance of such systems in terms of precision, speed, and resource optimization.

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