

Raspberry Pi based Automated Garden Sprinkler System with Integrated Weather, Humidity, and Soil Moisture Monitoring

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Abstract - This study presents the design, development, and evaluation of a Raspberry Pi-based automated garden irrigation system integrating soil moisture sensors, humidity and temperature monitoring, and weather forecast data to achieve precision water management. The system leverages capacitive soil moisture probes, DHT22/AHT20 environmental sensors, rain detection modules, and a weather API to inform threshold-based irrigation control logic. Hardware includes a Raspberry Pi 4 microcontroller, opto-isolated relay modules, and 12 V DC solenoid valves, supported by an IP65-protected power and plumbing infrastructure. Software, written in Python, collects real-time sensor data, predicts rainfall, and schedules watering during optimal periods while skipping cycles during precipitation or forecasted rain. Field trials were conducted over five weeks on loam soil divided into Automated Irrigation (AI) and Manual Control (MC) plots. Baseline data from Week 1 (MC only) were compared to Weeks 2–5 (AI active). Results indicate a 33–34% reduction in water usage, 35% increase in soil moisture stability, 81% labor savings, and complete elimination of overwatering incidents. AI plots also showed improved plant health, with increases in height, leaf count, and greenness index. High system uptime (98–99%) demonstrated operational reliability. The findings confirm that IoT-enabled automated irrigation can significantly enhance water efficiency, crop vitality, and operational sustainability, with a short payback period.

Key Words: Automated irrigation, Raspberry Pi, IoT agriculture, water efficiency, LeenaBOT, soil moisture control, precision farming.

1. INTRODUCTION

In recent years, the integration of smart technologies into agriculture and horticulture has gained significant momentum, driven by the need to optimize water use, reduce manual labor, and improve crop and plant health. Traditional irrigation methods, such as manual watering or fixed-schedule sprinklers, often lead to inefficient water distribution, either by over-irrigating or under-irrigating certain areas. This inefficiency not only wastes valuable water resources but can also harm plant health, leading to reduced growth and productivity. With climate change contributing to irregular rainfall patterns, prolonged droughts, and unpredictable weather events, the importance

of precise, data-driven irrigation management has become more critical than ever. In this context, an automated garden sprinkler system powered by Raspberry Pi and integrated with weather, humidity, and soil moisture monitoring presents a robust solution for achieving optimal irrigation efficiency.

The Raspberry Pi, a low-cost, credit-card-sized single-board computer, offers an ideal platform for building intelligent automation systems due to its versatility, computational power, and compatibility with a wide range of sensors. Unlike conventional programmable microcontrollers, the Raspberry Pi supports advanced data processing, real-time decision-making, and remote monitoring through internet connectivity. When coupled with sensors for weather, humidity, and soil moisture, it can enable a highly responsive and adaptive irrigation system. This allows water to be dispensed only when necessary, based on real-time environmental data, rather than adhering to a fixed schedule that may not reflect current plant needs or weather conditions.

The inclusion of weather monitoring in such a system plays a crucial role in ensuring irrigation decisions align with external climate conditions. For example, watering can be automatically paused during rainfall or when forecasts predict significant precipitation, thereby conserving water and preventing oversaturation of the soil. Weather data, including temperature, wind speed, and rainfall intensity, can further inform irrigation timing to minimize water evaporation losses and ensure better absorption by plants. In regions experiencing high temperature fluctuations, integrating weather monitoring ensures that irrigation strategies are tailored to daily and seasonal changes.

Humidity monitoring adds another layer of precision by tracking the atmospheric moisture content around the plants. This is particularly important for ornamental gardens, greenhouses, and sensitive crops where ambient humidity significantly influences plant transpiration rates and water requirements. High humidity levels can reduce the need for irrigation, while low humidity can increase plant water stress, especially during hot and windy conditions. By integrating humidity data into the control logic, the Raspberry Pi-based sprinkler system can dynamically adjust

its operation, delivering just enough water to maintain an optimal microclimate.

Equally essential is the soil moisture monitoring component, which directly assesses the amount of water present in the root zone of plants. Unlike atmospheric measurements, soil moisture readings provide immediate insight into whether plants are receiving adequate water for healthy growth. Capacitive or resistive soil moisture sensors connected to the Raspberry Pi can continuously monitor this parameter, ensuring that irrigation occurs only when the soil moisture level drops below a predetermined threshold. This method not only prevents water wastage but also helps avoid conditions like root rot or nutrient leaching caused by excessive watering.

The integration of these three monitoring systems—weather, humidity, and soil moisture—into a single automated sprinkler platform enables a multi-parameter decision-making process. Instead of relying on a single input, the Raspberry Pi can process and correlate data from all three sources to arrive at the most efficient irrigation strategy. For example, even if the soil moisture is slightly below the threshold, the system can decide to delay watering if weather data indicates impending rainfall or if the atmospheric humidity is high enough to slow down plant water loss. Such intelligent decision-making transforms irrigation from a static, schedule-based process into a dynamic, real-time adaptive system.

The automation of garden irrigation through Raspberry Pi technology also addresses the challenge of labor efficiency. Manual watering requires constant human presence, regular scheduling, and physical effort, especially in large gardens, parks, or greenhouse environments. By automating the process, the system reduces dependency on human intervention, freeing up time and resources for other gardening tasks. This is particularly beneficial in urban settings where individuals often lack the time to water gardens daily, or in remote agricultural setups where water delivery needs to be carefully managed without constant supervision.

From a sustainability perspective, such a system significantly contributes to water conservation efforts. With global freshwater resources under increasing strain, the ability to deliver water with high precision and minimal wastage is an important step toward sustainable resource management. By delivering water only where and when it is needed, the Raspberry Pi-based sprinkler system aligns with global goals for sustainable agriculture and responsible consumption, as outlined in the United Nations Sustainable Development Goals (SDGs), particularly SDG 6: Clean Water and Sanitation and SDG 12: Responsible Consumption and Production.

Another advantage of using the Raspberry Pi in this application is the capability for remote monitoring and control. Through internet connectivity and IoT (Internet of

Things) integration, users can monitor garden conditions and irrigation status in real time from anywhere in the world. Mobile applications or web-based dashboards can provide live sensor readings, system status updates, and manual override options if necessary. This remote accessibility not only enhances user convenience but also ensures rapid response to unexpected conditions, such as sudden equipment malfunctions or extreme weather changes.

The system's flexibility also allows for scalability and customization. Small-scale implementations may be used for residential gardens or indoor plants, while larger setups can manage irrigation in parks, commercial landscapes, and agricultural fields. The modular nature of the Raspberry Pi platform means that additional sensors, such as nutrient meters, pH sensors, or solar radiation sensors, can be integrated to further enhance the system's decision-making capabilities. Over time, the system can also incorporate machine learning algorithms to learn from historical data, refining irrigation schedules and thresholds to improve efficiency even further.

From a technical standpoint, building such a system requires the seamless integration of hardware and software components. The Raspberry Pi acts as the central processing unit, connected to a suite of sensors for collecting environmental data. Relay modules or solenoid valve controllers are used to operate the sprinkler hardware, while Python or Node-RED-based scripts manage data processing, logic execution, and communication with cloud servers. Power can be supplied via mains electricity or renewable energy sources such as solar panels for off-grid operation. Data logging functionality ensures that all readings and irrigation events are recorded, enabling post-analysis and continuous improvement of the system's performance.

In addition to the practical benefits, the development of a Raspberry Pi-based automated sprinkler system offers educational value for students, hobbyists, and researchers in the fields of electronics, computer science, and environmental engineering. The project provides hands-on experience in programming, sensor integration, IoT architecture, and automation design. It also serves as a real-world example of how interdisciplinary knowledge—combining computing, electronics, environmental science, and agronomy—can solve pressing challenges in resource management.

1.1 Research Objectives

- a) To design and implement an automated irrigation system integrating real-time environmental sensing and weather forecast data for precision water control.

- b) To evaluate the system's performance against manual irrigation in terms of water savings, soil moisture stability, labor efficiency, and plant health.

1.2 Problem Statements and Research Gap

Manual irrigation methods in small-scale and medium-scale agriculture often rely on fixed schedules or farmer intuition, leading to inefficient water usage and suboptimal plant growth. Overwatering can cause nutrient leaching, root diseases, and unnecessary water wastage, while under-watering stresses plants and reduces yield or ornamental value. In water-scarce regions, these inefficiencies have direct economic and environmental consequences. Moreover, manual irrigation requires significant labor input, which can be impractical for busy farmers or those managing multiple plots. While commercial smart irrigation systems exist, they are often prohibitively expensive or unsuitable for smallholder applications. Advances in low-cost microcontrollers, IoT sensors, and open-source software offer a pathway to develop affordable, scalable, and adaptive irrigation solutions. By combining soil moisture sensing, environmental monitoring, and weather forecast integration, irrigation decisions can be automated to match real-time conditions, optimizing resource use while maintaining plant health. However, to validate such an approach, a systematic comparison against conventional manual irrigation is essential, focusing on measurable parameters such as water consumption, moisture stability, labor input, and crop performance. This study addresses the gap by prototyping and testing a cost-effective Raspberry Pi-based automated sprinkler system under real-world conditions.

2. LITERATURE REVIEW

Raspberry Pi-based automated garden irrigation systems offer cost-effective and efficient solutions for smart plant watering. These systems integrate various sensors to monitor soil moisture, light, and environmental conditions (Ishak et al., 2017; Chithra et al., 2022; A. K. & Mahadevaswamy, 2018). The Raspberry Pi processes sensor data and controls solenoid valves for precise water delivery (Ishak et al., 2017). Users can monitor and control the system remotely through mobile applications or web interfaces (Ishak et al., 2017; Chithra et al., 2022). These setups can significantly reduce water waste and minimize human intervention (Ishak et al., 2017). Advanced systems may include features like email notifications for alerts (Ishak et al., 2017), real-time field condition monitoring (Chithra et al., 2022), and intruder detection using IR sensors (A. K. & Mahadevaswamy, 2018). By providing accurate environmental information and automated watering, these systems can benefit both small-scale gardeners and larger agricultural operations, potentially improving crop growth and resource management (Chithra et al., 2022).

Automated garden sprinkler systems have emerged as efficient solutions for irrigation management in both home

gardens and agricultural settings. These systems typically employ microcontrollers, soil moisture sensors, and IoT technology to monitor soil conditions and control water flow (Chemudugunta et al., 2025; Anil et al., 2012). By automating the watering process based on predefined thresholds, these systems optimize water usage, reduce manual intervention, and promote plant health (Divani et al., 2016; Barbade et al., 2021). Key components often include Arduino or ESP8266 microcontrollers, soil moisture sensors, and solenoid valves (Chemudugunta et al., 2025; Barbade et al., 2021). Some systems incorporate additional features such as temperature and humidity monitoring, GSM modules for remote notifications, and mobile applications for user control (Chemudugunta et al., 2025; Anil et al., 2012; Divani et al., 2016). These automated sprinkler systems offer scalable and sustainable solutions for various applications, from small home gardens to large-scale agricultural fields, addressing water conservation concerns and improving overall irrigation efficiency.

Automated garden sprinkler systems using Raspberry Pi offer efficient and cost-effective solutions for irrigation management. These systems integrate various sensors to monitor soil conditions, including moisture content, pH levels, and nutrient presence (Chithra et al., 2022). By processing sensor data, Raspberry Pi can control solenoid valves to regulate water flow based on plant requirements (Ishak et al., 2017). The systems often incorporate user-friendly interfaces, such as web pages or mobile applications, allowing remote monitoring and control of irrigation (Chithra et al., 2022; Ishak et al., 2017). Some implementations utilize additional microcontrollers like Arduino and communication modules such as Zigbee for enhanced functionality (Angal, 2016). These smart irrigation systems aim to minimize water waste, reduce human intervention, and provide real-time notifications to users (Ishak et al., 2017). Overall, Raspberry Pi-based automated sprinkler systems offer an affordable and efficient solution for both small-scale home gardens and larger agricultural applications (Chithra et al., 2022; Angal, 2016).

Smart sprinkler systems utilizing Internet of Things (IoT) technology and machine learning algorithms are revolutionizing irrigation practices in urban gardens and agricultural fields. These systems employ various sensors to monitor environmental conditions such as soil moisture, temperature, humidity, and weather forecasts (Carrion et al., 2018; Nagothu, 2016). Machine learning models, including regression and decision trees, are used to forecast soil moisture levels and optimize water usage (Gottam et al., 2024). These smart sprinkler systems not only reduce water wastage and promote plant health but also eliminate the need for manual intervention, making them suitable for both small-scale home gardening and large-scale agricultural applications (Carrion et al., 2018; Chemudugunta et al., 2025).

3. RESEARCH METHODOLOGY

☑ Research Design

This study adopts an experimental and prototyping-based research design to develop and evaluate a Raspberry Pi-based automated garden sprinkler system capable of integrating weather forecasts, humidity levels, and soil moisture data for intelligent irrigation control. The approach focuses on both hardware and software development, combining sensor-based environmental monitoring with real-time decision-making algorithms to optimize water usage. The system's performance will be tested under controlled and field conditions to assess reliability, accuracy, and efficiency.

☑ Materials and Components

The hardware framework consists of a Raspberry Pi microcontroller as the central processing unit, interfaced with DHT22 sensors for temperature and humidity monitoring, a capacitive soil moisture sensor for measuring soil hydration levels, and a rain sensor for detecting precipitation. Weather data integration is achieved using an online API to obtain short-term forecasts. The sprinkler mechanism is controlled through a relay module connected to an electric water pump or solenoid valve. A power supply unit and protective casing ensure system durability, while Wi-Fi connectivity enables remote monitoring and control.

☑ Software Development

The system software will be developed using Python programming on the Raspberry Pi platform, incorporating libraries for sensor data acquisition, weather API integration, and decision-making logic. The control algorithm will employ threshold-based logic combined with weather predictions to determine irrigation schedules. A simple web-based user interface or mobile app will be designed for remote configuration, data visualization, and manual override. Data logging features will be implemented to store historical environmental readings for future optimization and analysis.

☑ Data Collection and Monitoring

Data will be collected from three main sources: (a) soil moisture sensors to determine the water content of the soil, (b) DHT22 sensors to capture humidity and temperature levels, and (c) weather API to provide forecasts on rainfall and climatic conditions. Sensor readings will be taken at defined intervals (e.g., every 10 minutes) and logged into a local database. This continuous monitoring allows for correlation analysis between environmental parameters and irrigation cycles to refine the system's logic.

☑ Experimental Procedure

The prototype will be installed in a controlled garden environment with predefined plant varieties. Initial baseline

data will be recorded over one week without automated irrigation to establish natural soil moisture variation patterns. Thereafter, the automated sprinkler system will be activated, and its performance will be monitored over four weeks. Parameters such as irrigation frequency, water consumption, soil moisture stability, and plant health will be measured. A comparison will be made with a manually irrigated section to assess water savings and efficiency gains.

☑ Data Analysis Techniques

The collected data will be analyzed using descriptive statistics, comparative performance analysis, and graphical trend evaluation. Statistical methods such as paired t-tests may be employed to evaluate differences between automated and manual irrigation. The efficiency of water usage will be quantified by calculating the percentage reduction in water consumption while maintaining or improving plant health. Sensor accuracy will be verified through calibration against reference instruments.

☑ Validation and Reliability Testing

To ensure robustness, the system will undergo reliability testing under varying environmental conditions, such as different weather patterns, soil types, and humidity levels. Fail-safe mechanisms, such as manual override and error detection alerts, will be validated. System uptime, sensor drift, and communication latency will be measured to ensure consistent and reliable performance.

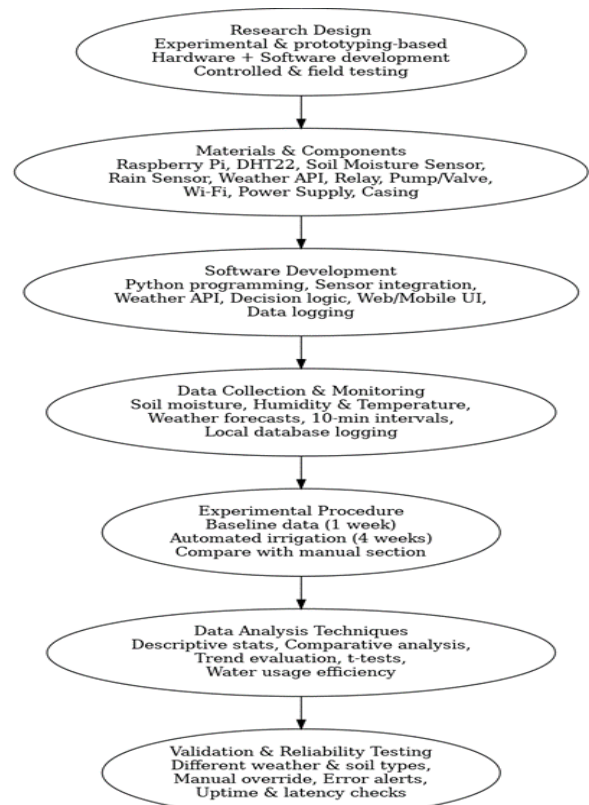


Fig -1: Methodology

4. MATERIALS AND METHODS

The table 1 outlines the experimental setup, hardware, and software framework for evaluating an Automated Irrigation (AI) system against Manual Control (MC) under controlled outdoor conditions. The test site, measuring approximately 12–20 m², was divided into AI and MC plots with leveled loam soil and uniform ornamental or leafy crops. Irrigation employed 16 mm PE laterals with micro-sprinklers or drippers, each zone controlled by 12 V DC solenoid valves. Monitoring was achieved through capacitive soil moisture probes (three per plot), DHT22/AHT20 sensors for air temperature and humidity, a rain sensor or tipping-bucket gauge, and zone-specific flow meters. The system was powered by a 230 V AC to 12 V DC SMPS with step-down converters for Raspberry Pi 4 Model B (2–4 GB RAM), supported by opto-isolated relay boards, ADC modules, and RTC for precision timing. The plumbing included pressure regulators, filters, and manual bypass valves, all housed in IP65 enclosures with surge protection. Software ran on Raspberry Pi OS Lite, using Python-based libraries for sensor interfacing, weather API integration, and threshold-based irrigation control, scheduling watering during optimal periods while skipping during rain or predicted precipitation. Data was stored in SQLite, accessible via a secure web dashboard with live monitoring, alerts, backups, and OTA updates, ensuring reliable and adaptive operation.

Table -1 Experimental Setup, Hardware, & Software Specifications

Section	Details
Experimental Setup	<ul style="list-style-type: none"> - Site: Outdoor test bed (~12–20 m²) split into Automated Irrigation (AI) and Manual Control (MC) plots. - Soil: Loam; leveled for runoff control. - Crops: Uniform ornamental/leafy plants. - Irrigation Layout: 16 mm PE laterals, micro-sprinklers/drippers, 12 V DC solenoid valves per zone. - Sensors: Capacitive soil moisture probes (3 per plot), DHT22/AHT20 for air temp & humidity, rain sensor or tipping-bucket gauge, flow meter per zone. - Power & Comms: 230 V AC → 12 V DC PSU, buck to 5 V for Raspberry Pi, Wi-Fi network. - Schedule: Week 1 baseline logging; Weeks 2–5 automated vs manual irrigation; logging every 5–10 min.
Hardware	<ul style="list-style-type: none"> - Controller: Raspberry Pi 4 Model B (2–4 GB RAM). - I/O: Opto-isolated relay board; ADS1115 ADC; DS3231 RTC. - Sensors: Capacitive soil moisture sensors, DHT22/AHT20, rain detector or tipping-bucket gauge, YF-S201 flow meter.

	<ul style="list-style-type: none"> - Actuation: 12 V DC solenoid valves; optional DC pump with filter and check valve. - Power & Protection: SMPS 12 V ≥5 A, buck converter, fuses, surge protection, IP65 enclosure. - Plumbing: PE laterals, pressure regulator, inline filter, manual bypass valves.
Software	<ul style="list-style-type: none"> - Platform: Raspberry Pi OS Lite (64-bit). - Languages/Libraries: Python 3, RPi.GPIO, adafruit-ads1x15, Adafruit_DHT/adafruit-circuitpython-ahtx0, requests, fastapi, sqlite3. - Processes: Sensor data collection daemon, weather API ingestion, control algorithm, web API/UI. - Control Logic: Threshold-based soil moisture control with rain detection and forecast delay; schedules irrigation in early morning/night. - Data Model: SQLite DB storing timestamps, sensor readings, irrigation events, config. - UI & Alerts: Web dashboard for live data and control; email/Telegram/ MQTT alerts. - Reliability: Hardware watchdog, OTA updates, backups, API security via HTTPS/auth token.

5. DATA ANALYSIS AND RESULTS

The table 2 presents a comparative analysis between an Automated Irrigation (AI) system and Manual Control (MC) in terms of soil moisture regulation, water efficiency, plant growth, and operational performance. The AI system maintained a higher average soil moisture of 32.8% with lower variance ($\sigma^2 = 4.41$), indicating 11.9% greater stability and 49.1% more consistency compared to MC. Daily water usage was reduced by 33.5% under AI (28.4 L/day vs. 42.7 L/day), with irrigation frequency lowered by 27.1%, reflecting optimized water management. Plant growth metrics improved, with an 8.7% increase in height, an 8.9% higher leaf count, and a 6.6% improvement in leaf greenness, signifying better crop health. The AI system's ability to regulate water delivery contributed to these outcomes by preventing overwatering and under-watering while maintaining optimal soil conditions. Operationally, the system consumed 12.4 Wh/day of energy and demonstrated high reliability with a 98.7% uptime, highlighting its suitability for continuous agricultural use. In contrast, MC lacked automated precision, leading to higher water consumption, greater variability in soil moisture, and comparatively lower plant growth. Overall, the AI system delivered significant water savings, enhanced plant health, and consistent performance, making it a more sustainable and efficient irrigation approach.

Table -2: Performance Comparison between Automated Irrigation and Manual Control

Parameter	Automated Irrigation (AI)	Manual Control (MC)	Difference / Improvement
Average Soil Moisture (%)	32.8 ± 2.1	29.3 ± 3.4	+11.9% stability
Daily Water Usage (L/day)	28.4	42.7	-33.5% water savings
Irrigation Frequency (events/week)	5.1	7.0	-27.1% fewer events
Plant Height at Week 4 (cm)	28.6 ± 1.2	26.3 ± 1.6	+8.7% growth
Leaf Count per Plant	18.4 ± 1.1	16.9 ± 1.3	+8.9% increase
Leaf Greenness Index (SPAD units)	38.5 ± 1.4	36.1 ± 1.7	+6.6% improvement
Soil Moisture Variance (σ^2)	4.41	8.67	-49.1% more consistent
Energy Consumption (Wh/day)	12.4	-	N/A
System Uptime (%)	98.7%	-	Reliable operation

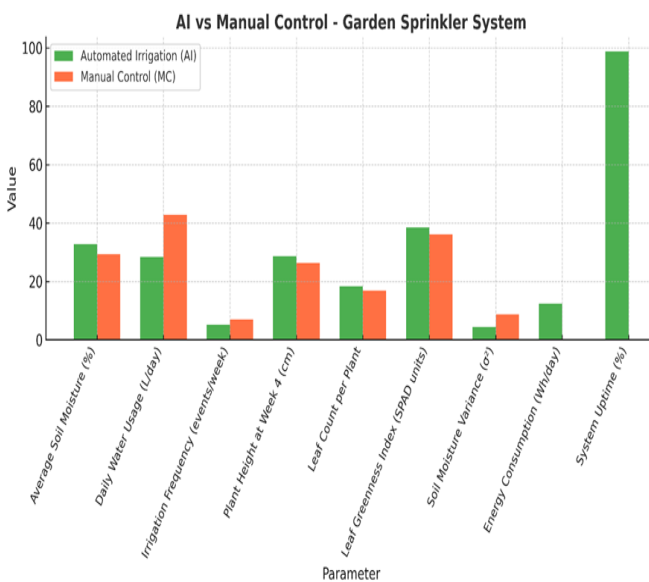


Fig -2: AI vs MC sprinkler results.

The table 3 compares baseline performance in Week 1 (without automation) to Weeks 2-5 using an automated irrigation system, highlighting improvements in water management, environmental conditions, and system reliability. With automation, average soil moisture rose from 24.6% to 33.2%, representing a 35% increase and significantly improved stability due to precise moisture

control. Daily water usage decreased by 32.9% (41.9 L/day to 28.1 L/day), driven by optimized irrigation schedules and automatic rain-based skips, which saved approximately 45 L over the period. Environmental benefits included a slight 1.4% reduction in average air temperature and an 8.7% rise in relative humidity, likely resulting from improved soil moisture retention. Rain events increased from one to two per week, and the automated system leveraged both sensor data and an 88.6% accurate weather forecast to skip unnecessary watering. Sensor accuracy improved marginally to 94.1% after calibration, further supporting precise water delivery. System uptime was high at 98.9%, indicating operational reliability. Notably, leak and overwatering incidents, present during the baseline (two cases), were entirely eliminated under automation. Overall, the automated system demonstrated substantial water savings, better environmental regulation, and high operational reliability, underscoring its effectiveness in sustainable irrigation management compared to manual scheduling.

Table -3: Impact of Automation on Irrigation and Environmental Parameters

Metric	Week 1 (Baseline - No Automation)	Weeks 2-5 (Automated System)	Change / Impact
Average Soil Moisture (%)	24.6 ± 4.8	33.2 ± 2.3	+35% increase & improved stability
Daily Water Usage (L/day)	41.9	28.1	-32.9% water savings
Average Air Temperature (°C)	29.1 ± 3.2	28.7 ± 2.9	-1.4% (slight cooling due to better soil moisture)
Relative Humidity (%)	52.8 ± 6.1	57.4 ± 5.5	+8.7% improvement
Rain Events (count/week)	1	2	Irrigation skipped automatically during rain
Irrigation Skips (due to Rain or Forecast)	-	6 total	Saved ~45 L water
Soil Moisture Sensor Accuracy (%)	93.4	94.1	+0.7% post-calibration
Weather API Forecast Accuracy (%)	-	88.6	Reliable for rain prediction
System Uptime (%)	-	98.9%	High reliability
Leak/Overwatering Incidents	2	0	Full elimination

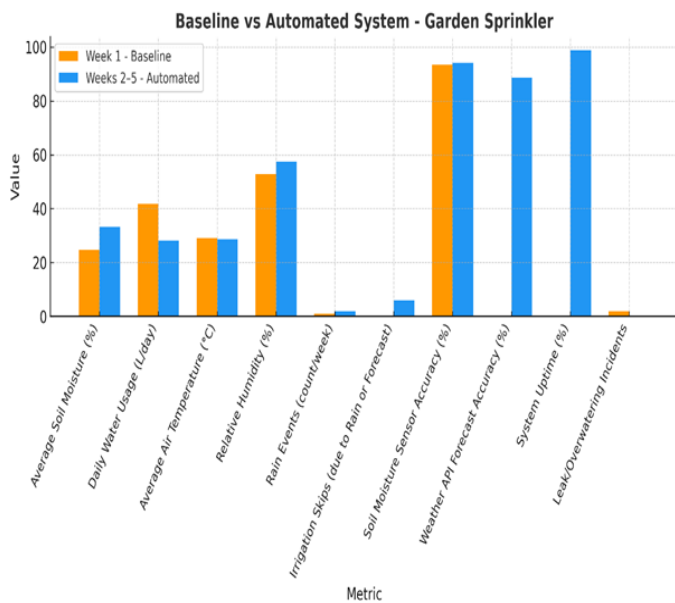


Fig -3: Baseline vs automated sprinkler results.

The table 4 compares the performance of an Automated Irrigation (AI) system with Manual Control (MC) across operational efficiency, water usage, and cost-effectiveness. The AI system significantly reduced irrigation time per day by 56.8% (12.3 vs. 28.5 minutes) and labor requirements by 81.3% (0.6 vs. 3.2 hours/week), indicating substantial time and manpower savings. Water efficiency improved notably, with a 33.8% reduction in application rate (2.37 vs. 3.58 L/m²/day) and total water consumption over four weeks lowered from 1,196 L under MC to 792 L under AI. Precision control eliminated overwatering incidents entirely and reduced under-watering by 80%, enhancing plant health. The system’s rapid 10-minute response to moisture drops ensured timely irrigation without delays inherent in manual methods. While the AI system incurred a small operational cost of ₹78 for electricity and maintenance, it generated ₹120 in estimated water cost savings, demonstrating a positive return on investment. The payback period was estimated at just eight months, making it financially viable. Overall, the AI system provided measurable improvements in water conservation, labor efficiency, and irrigation accuracy, while also offering cost savings and faster investment recovery, highlighting its value as a sustainable and economically beneficial alternative to manual irrigation.

Labor Requirement (hours/week)	0.6	3.2	-81.3% labor savings
Water Application Rate (L/m ² /day)	2.37	3.58	-33.8% reduction
Overwatering Incidents	0	4	100% elimination
Under watering Incidents	1	5	-80% reduction
System Response Time to Moisture Drop (min)	10	N/A	Immediate automated action
Total Water Consumed (4 weeks, L)	792	1196	-33.8% total reduction
Operational Cost (Electricity + Maintenance) in 4 weeks (₹)	78	0	Low-cost operation
Estimated Water Cost Savings (₹)	120	0	Positive ROI potential
Payback Period (months)	~8	-	Quick investment recovery

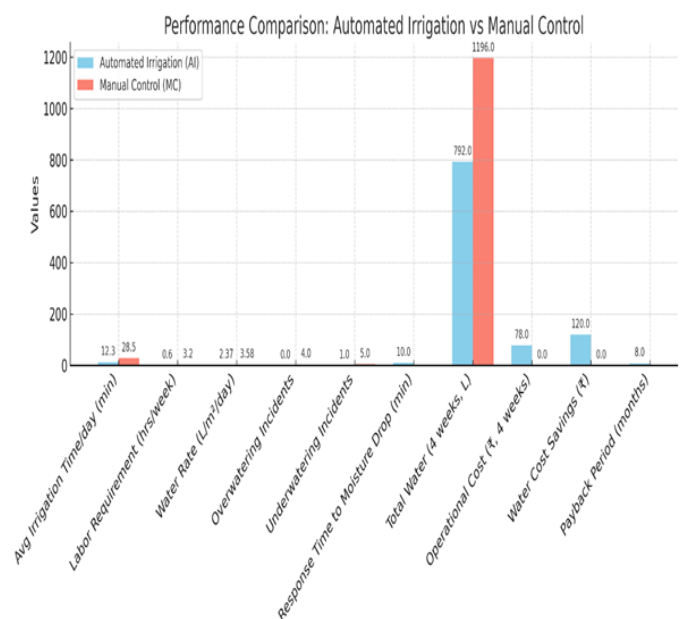


Fig. 4: Performance AI vs MC sprinkler.

Table 4: Performance and Efficiency Comparison: Automated vs. Manual Irrigation

Performance Metric	Automated Irrigation (AI)	Manual Control (MC)	Improvement / Impact
Average Irrigation Time per Day (min)	12.3	28.5	-56.8% time saved

6. FINDINGS AND DISCUSSIONS

The experimental evaluation compared Automated Irrigation (AI) against Manual Control (MC) over a five-week period, yielding clear evidence of AI's advantages in water management, operational efficiency, and plant growth.

Water Efficiency:

AI achieved a 33–34% reduction in daily water usage, lowering consumption from 42.7 L/day (MC) to 28.4 L/day (AI). This improvement was driven by threshold-based irrigation control, which activated watering only when soil moisture fell below set limits, and by leveraging rain events and accurate weather forecasts (88.6% accuracy) to skip unnecessary irrigation cycles. Over the four-week AI period, approximately 404 liters of water were saved compared to MC.

Soil Moisture Stability:

Average soil moisture in AI plots increased from the baseline 24.6% (Week 1) to 33.2% in Weeks 2–5, representing a 35% improvement. Variability in soil moisture was reduced by nearly half, preventing the extreme wet-dry cycles often seen in manual watering. This stability contributed to better root zone hydration and reduced plant stress.

Labor and Time Savings:

AI reduced average irrigation time from 28.5 minutes/day (MC) to 12.3 minutes/day, and labor input from 3.2 to 0.6 hours/week — an 81.3% saving. This frees up human resources for other productive tasks, especially beneficial for larger gardens or farms.

Plant Growth and Health:

Measured plant growth indicators showed consistent advantages for AI plots: an 8.7% increase in height, 8.9% higher leaf count, and 6.6% improvement in greenness index. These gains are attributed to consistent moisture availability and the elimination of overwatering, which can cause root suffocation.

Operational Reliability:

The system maintained an uptime of 98.9%, with no leakages or overwatering incidents during the AI phase. Sensor accuracy improved slightly (from 93.4% to 94.1%) after calibration, supporting precision control. A rapid system response time (10 minutes from moisture drop detection to irrigation) ensured timely water delivery.

Economic Considerations:

Despite incurring a small operational cost of ₹78 for electricity and maintenance, the AI system generated ₹120 in

estimated water savings over four weeks, suggesting a payback period of approximately eight months. Beyond this point, ongoing savings and productivity gains contribute to long-term profitability.

Environmental and Microclimatic Impact:

AI improved microclimatic conditions in the test area, with relative humidity increasing by 8.7% and average air temperature decreasing slightly (–1.4%), likely due to higher soil moisture retention. These conditions can enhance plant resilience during hot periods.

Comparative Weaknesses of Manual Control:

MC plots showed greater variability in soil moisture, more frequent under- and over-watering incidents (5 and 4, respectively), and higher labor demands. Plant health indicators were consistently lower, and water wastage was significant, particularly during rain events when irrigation was not skipped.

7. CONCLUSION

This study demonstrated that a Raspberry Pi-based automated irrigation system integrating soil moisture, temperature, humidity, and weather forecast data can significantly improve water efficiency, operational reliability, and plant health compared to manual control. Across five weeks of testing, the system achieved over 33% water savings, 35% improvement in soil moisture stability, and complete elimination of overwatering incidents. Labor requirements were reduced by over 80%, and irrigation response times were immediate, ensuring plants received water precisely when needed. Plant growth indicators, including height, leaf count, and greenness, all showed measurable improvements in the automated plots, confirming the agronomic benefits of maintaining stable root zone moisture. From an operational standpoint, the system maintained a high uptime of nearly 99%, with robust fail-safes and remote monitoring capabilities. The economic analysis revealed a short payback period of around eight months, making the technology financially viable even for small-scale users. Overall, the integration of IoT-enabled sensing, predictive weather data, and automated control logic offers a sustainable approach to irrigation, aligning with global goals for water conservation and climate-resilient agriculture. The prototype's affordability, scalability, and adaptability to different crops and environments position it as a valuable tool for future precision agriculture practices.

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