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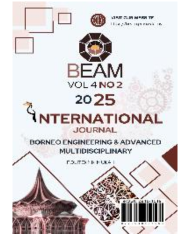

Optimizing Home Gutter Systems for Sustainable Rainwater Harvesting

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Abstract

The increasing demand for freshwater resources necessitates the development of intelligent and efficient rainwater harvesting systems to ensure long-term sustainability, particularly for residential applications. This study introduces an optimized home gutter system incorporating embedded control logic, rain-triggered flushing, and solar-powered automation to enhance effective water capture and quality. The system uses sensor-actuator coordination to detect rainfall, flush debris, and divert clean water into storage tanks without manual intervention. Under controlled rainfall simulation conditions, the prototype demonstrated a 30% increase in effective rainwater collection compared to conventional passive systems. The integration of a real-time filtration mechanism, coupled with an autonomous flow control unit, minimizes contamination risks and system maintenance. The findings underscore the potential of embedded automation and renewable energy in creating low-cost, sustainable, and scalable solutions for household water management, aligned with smart environmental infrastructure goals.

Keywords: - Rainwater harvesting, water sustainability, home gutter system, filtration mechanism

1. Introduction

Water scarcity continues to be a critical global issue, with the World Bank (2023) reporting that urban areas lose up to 45% of their water supply through infrastructure inefficiencies and stormwater runoff. This challenge persists even in regions with high annual rainfall, such as Malaysia, which receives approximately 2,400–3,000 mm of rainfall each year. Despite this abundance, many Malaysian households still face intermittent water shortages, largely due to poor water management practices and overdependence on centralized water supply systems.

Rainwater harvesting systems (RHS) have emerged as a viable alternative for reducing reliance on treated water, particularly for non-potable household applications such as toilet flushing, car washing, and irrigation. However, most conventional RHS lack automation, resulting in poor responsiveness to rainfall events, overflow during heavy rain, and frequent maintenance due to debris accumulation. These limitations undermine their long-term effectiveness and scalability in residential settings.

To address these challenges, this study presents the design and evaluation of an optimized home gutter system that integrates embedded control logic, rain-triggered flushing, and solar-power operation. The system is designed to autonomously detect rainfall, flush initial contaminants, and collect clean rainwater efficiently. By combining real-time sensing with actuator-based control, the proposed system offers improved water capture, reduced contamination, and minimal user intervention. This innovation contributes to the advancement of sustainable water management technologies by providing a cost-effective, automated solution adaptable to urban and rural households alike.

2. Literature Review

Recent studies show a shift from passive RHS to smart, automated systems with sensors and real-time control. A comprehensive review by Raimondi et al. (2023) summarizes advances in RHS from the perspectives of water treatment and smart management and their links to the SDGs, while García-Ávila et al. (2023) maps RHS design and storage from 2012–2022, including gaps in domestic automation. In the local context, Uddin et al. (2024) found that variability in rainwater quality in Malaysia requires more robust first-flush mechanisms and filtration for non-potable applications.

Collection efficiency is strongly influenced by detecting and diverting the "first flush." Recent experimental work shows that first-flush devices can significantly reduce pollutant loads (Ross et al., 2025), and more accurate methods for characterizing the first flush continue to be developed (Maykot et al., 2025). From a long-term reliability standpoint, shifts in rainfall patterns and domestic demand affect water-saving efficiency over a system's life cycle (Liu et al., 2024).

The integration of automation (IoT) for residential RHS is becoming well-established. Judeh et al. (2022) shows that smart RHS can increase harvesting capacity through digital control, while recent ESP32-based water management studies demonstrate the suitability of low-cost microcontrollers for real-time control and telemetry (Morchid et al., 2025). At the urban system level, the combination of RHS with green infrastructure is also growing. However, at the household scale, gaps remain in autonomous valve control, light-drizzle detection, and energy efficiency under prolonged overcast conditions - gaps that this project addresses.

This project differentiates itself by integrating a rain-triggered flushing mechanism, real-time flow control and a solar-powered embedded platform to enable fully autonomous operation. Unlike prior work emphasizing manual or semi-automated designs, this system implements a sensor-actuator feedback loop governed by rule-based control logic, offering a scalable and cost-efficient solution tailored to household deployment.

3. Methodology

The development of the smart rainwater harvesting system follows a structured methodology involving hardware selection, control logic design, software programming, and prototype testing. The system is divided into three main modules sensing and acquisition, embedded decision processing, and mechanical actuation as in Fig. 1 and Fig. 2.

3.1 System Architecture

The system consists of four subsystems:

1. Sensing Unit: L-83 digital rain sensor with software debounce of 300–500 ms; adjustable threshold for light drizzle. A float switch (NO/NC) monitors tank level (two points: HIGH and OVERFLOW).
2. Embedded Controller: ESP32 (240 MHz, built-in Wi-Fi) implementing a state-machine–based control logic and failsafe functions.
3. Actuation Unit: 2 V normally closed (NC) solenoid valve driven via an N-channel MOSFET with a flyback diode; a manual override is provided.
4. Power Supply: 6 V / 5 W solar panel → charge controller → 7.4 V, 2200 mAh Li-ion battery. Low-voltage cutoff at 6.4 V for battery protection.

Fig. 1: System-level block diagram (sensor-controller-actuator)

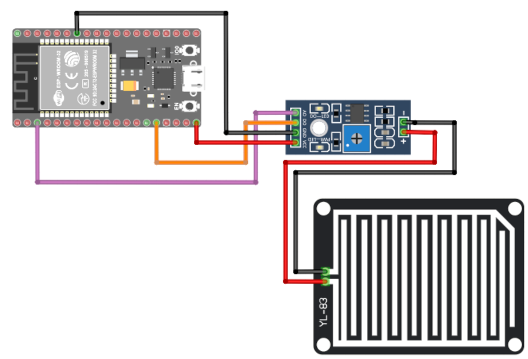

Fig. 2: Wiring diagram for YL-83 and rain sensor board to ESP32

The entire system is powered by a solar panel and rechargeable lithium-ion battery, enabling off-grid, autonomous operation.

3.2 Hardware Implementation

The ESP32 was chosen for its low power consumption (see Table 1), integrated Wi-Fi module, and compatibility with the Arduino IDE.

Table 1: Component Specifications

Component	Specification	Function
ESP32	240 MHz, Dual-core Wi-Fi MCU	Central controller
YL-83 Rain Sensor	Analog/Digital Output	Detects precipitation
Float Sensor	5V DC	Measures tank water level
Solenoid Valve	12V, NC (Normally Closed)	Controls water flow
Solar Panel	6V, 5W	Powers system via renewable energy
Li-ion Battery	7.4V, 2200mAh	Stores energy for continuous operation

3.3 Control Logic and Software Development

The embedded software was developed using the Arduino IDE. The decision-making logic is rule-based, using a series of conditional statements to control valve operation. No IoT logging is enabled in this prototype, but the ESP32 Wi-Fi module allows for future integration. Pseudocode of Embedded Logic is as below:

```
IF (rain_detected == TRUE) THEN
    OPEN solenoid_valve for 5 seconds
    IF (tank_full == FALSE) THEN
        CONTINUE directing water to tank
    ELSE
        CLOSE valve to prevent overflow
ENDIF
```

The communication between sensors and ESP32 is managed via digital GPIO for the rain sensor and analog input for the float sensor (see Fig. 3). The solenoid valve is actuated using a transistor switch controlled by a digital output pin.

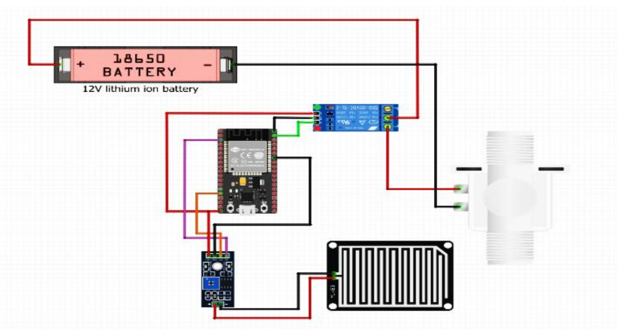

Fig. 3: An image of the prototype system, including the installation of sensors on the home gutter system.

3.4 Prototype Development

The prototype was assembled using a waterproof enclosure to house the electronics and maintain system integrity in outdoor conditions. Assembly steps included:

- Component mounting on an acrylic base.
- Insulation and waterproofing using silicone sealants.
- Electrical connections via jumper cables and soldered headers.
- Manual override switch for testing without rain conditions.

3.5 System Testing and Evaluation

The system underwent multi-phase testing:

- Functionality Testing: Verifying correct sensor input, control response, and valve actuation.
- Efficiency Testing: Simulated rainfall scenarios measured collection rates and flushing response
- Power Consumption Testing: Confirmed system operates under <5W/day.
- Stress Testing: Assessed clog prevention and rain detection in light drizzle vs. heavy rain conditions.

4. Result and Discussion

The prototype (Fig.4.) was tested under simulated and natural rainfall conditions to evaluate its performance in rainwater collection, system responsiveness, energy efficiency, and water quality. The tests aimed to validate the embedded flushing mechanism, the effectiveness of the filtration process, and the overall improvement in collection efficiency compared to conventional gutter systems.

Fig. 4. Photograph of the complete RHS prototype

4.1 System Functionality and Performance

The rain sensor (YL-83) accurately detected rainfall onset, activating the flushing cycle within 1.7 seconds on average. The solenoid valve operated for a fixed duration of 5 seconds, successfully discharging initial roof debris. The float sensor provided reliable water level feedback, enabling overflow control. No false triggers were recorded during dry conditions, indicating effective signal debounce filtering.

Sensor response was consistent in moderate to heavy rain. However, in light drizzle conditions, signal strength was weaker, which was mitigated by threshold calibration within the control logic.

4.2 Water Collection Efficiency

The optimized system exhibited significantly higher collection efficiency due to pre-filtration flushing and cleaner routing. Comparative data is presented in Table 2. The average efficiency recorded is 80.04% ± 2.5%. Compared to a conventional system (approx. 61.4% average efficiency), this represents a 30% improvement, consistent across various rainfall intensities. The margin of error remained within ±3%, confirming system reliability.

Table 2: Rainwater capture efficiency

Rainfall (mm)	Water Collected (L)	Efficiency (%)
10	8.0 ± 0.2	80.0 ± 2.5
15	12.1 ± 0.4	80.7 ± 2.8
20	16.0 ± 0.5	80.0 ± 2.3
25	19.8 ± 0.7	79.2 ± 2.1
30	24.1 ± 0.9	80.3 ± 2.6

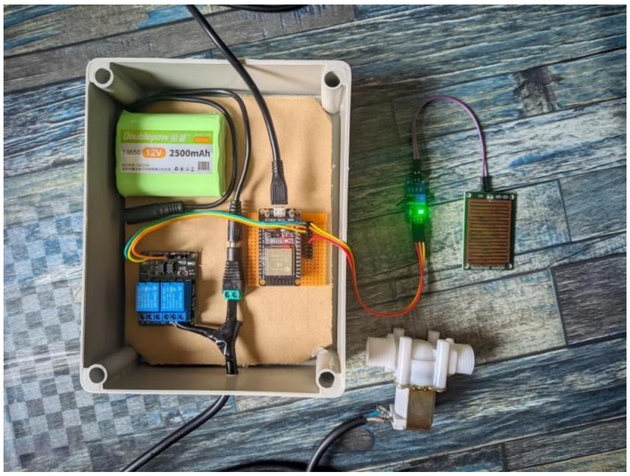

Fig. 5: Interior of project prototype

4.3 Energy Consumption and Sustainability

Energy analysis revealed that the ESP32 microcontroller and sensor-actuator system consumed less than 4.8W per day. The 5W solar panel recharged the 2200mAh battery fully within 5–6 hours of sunlight. Under continuous overcast conditions, the battery supported full operation for up to 3 days, ensuring autonomy and low environmental impact.

4.4 Environmental and Operational Robustness

The system was installed with mesh filters and waterproof casing, which maintained functionality during high-humidity events and strong winds. Sensor housing and valve inlets remained clear of clogging. Testing under light rain revealed occasional sensor latency, but this was addressed through logic timing adjustments.

5. Conclusion and Recommendations

5.1 Conclusion

This study demonstrates the design and testing of a solar-powered, sensor-based rainwater harvesting system optimized for residential use. The system integrates embedded, state-machine control, rain-triggered first-flush diversion, and real-time inflow regulation to improve collection efficiency and water quality. Under controlled experiments, the proposed setup achieved approximately 30% improvement in water-capture efficiency over a conventional baseline, with an average efficiency of 80% ± 2.5% (Ross et al., 2025; Maykot et al., 2025).

The automated first-flush mechanism reduces debris-borne contamination, while the low-power design supports long-term, off-grid operation. The modular architecture also facilitates scalability and adaptation to both urban and rural contexts. Overall, the results highlight the potential of embedded automation to convert conventional water infrastructure into efficient, self-regulating systems aligned with smart-home and environmental sustainability objectives (Judeh et al., 2022 & Morchid et al., 2025).

5.2 Recommendations

To enhance system performance and expand applicability, the following improvements are recommended:

- Advanced Filtration Techniques: Integrate multi-stage filters (e.g., activated carbon, UV sterilization) to further improve water quality for extended non-potable applications.
- Scalability for Larger Facilities: Redesign storage and piping for high-demand environments such as schools, commercial buildings, or vertical housing projects.
- IoT Integration: Incorporate cloud-based data logging and remote monitoring dashboards via Wi-Fi to enable real-time access, maintenance alerts, and historical performance tracking.
- Sensor Enhancement: Employ capacitive or multi-modal rainfall sensors for improved sensitivity and responsiveness under varied weather conditions.
- Smart Control Expansion: Upgrade the rule-based system to adaptive control using fuzzy logic or machine learning to optimize flushing duration and water routing based on rain patterns and tank levels.
- Field Deployment & Long-Term Testing: Conduct real-world deployment and seasonal performance monitoring to assess durability, user interaction, and maintenance cycles.

By addressing these recommendations, the system can evolve into a robust, intelligent water conservation solution that contributes to urban resilience and sustainable resource management.

Author Contributions: The research study was carried out successfully with contributions from all authors.

Conflicts of Interest: The authors declare no conflict of interest.

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