IoT-Enabled Automated Solar Panel Cleaning and Real-Time Performance Monitoring System for Enhanced Photovoltaic Efficiency

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Abstract

Solar energy is one of the most promising and rapidly expanding renewable energy sources worldwide; however, its practical efficiency is significantly hampered by dust and debris accumulation on photovoltaic (PV) panel surfaces. This paper presents the design, simulation, and hardware implementation of an Internet of Things (IoT)-enabled automated solar panel cleaning and real-time performance monitoring system aimed at addressing this critical challenge. The proposed system integrates an Arduino Uno microcontroller with a suite of sensors — including a Light Dependent Resistor (LDR), a dust sensor, a temperature sensor (LM35), and voltage/current transducers — to continuously assess panel soiling levels and environmental conditions. Upon detection of dust accumulation beyond a defined threshold, an automated cleaning mechanism comprising a DC motor-driven wiper and a relay-controlled water pump is activated to restore panel cleanliness. Simultaneously, the IoT cloud platform enables real-time remote monitoring of key performance parameters — including output voltage, current, power generation, temperature, and efficiency — through a web portal and mobile application interface. Simulation was carried out in the Proteus environment to validate system logic prior to physical implementation. Experimental results demonstrate that the automated cleaning mechanism yields a 12–18% improvement in energy output compared to uncleaned panels operating under equivalent irradiance conditions. Predictive maintenance capabilities embedded within the cloud analytics further reduce operational downtime and extend panel lifespan. This work contributes a cost-effective, scalable, and sustainable solution for optimising solar energy harvesting in both residential and commercial photovoltaic installations.

Keywords

Solar photovoltaic system; Internet of Things (IoT); automated cleaning mechanism; dust monitoring; Light Dependent Resistor (LDR); Arduino Uno; real-time performance monitoring; cloud analytics; predictive maintenance; renewable energy efficiency.

1. Introduction

The global demand for clean, sustainable energy has positioned solar photovoltaic (PV) technology as one of the most significant contributors to the renewable energy landscape. According to the International Energy Agency (IEA), solar PV capacity has grown exponentially over the past decade, with installed capacity exceeding 1 TW globally by 2023 [1]. Despite this growth, the practical efficiency of PV systems remains a persistent concern, as real-world operating conditions deviate

substantially from standard test conditions (STC). Among the various factors that degrade PV performance — including temperature rise, shading, and component ageing — the soiling of panel surfaces due to dust, pollen, bird droppings, and other airborne particulates is one of the most pervasive and economically significant [2].

Research has consistently demonstrated that dust accumulation on PV panels can reduce energy output by 10–30% under typical outdoor conditions, with losses exceeding 50% in arid and desert environments characterised by high dust storm frequency [3]. In regions such as the Middle East, North Africa, South Asia, and parts of India — where solar irradiance is high but dust loading is also substantial — the economic impact of soiling losses is considerable. Consequently, maintaining panel cleanliness through regular and effective cleaning is essential for maximising return on investment and ensuring grid reliability.

Traditional cleaning approaches — predominantly manual washing with water and cloth — are labour-intensive, water-consumptive, and operationally inefficient, particularly for large-scale solar farms [4]. The logistical challenges of scheduling cleaning for hundreds or thousands of panels across geographically distributed installations make manual methods increasingly impractical. Furthermore, the use of large volumes of water raises serious environmental and sustainability concerns, especially in water-scarce regions.

The emergence of the Internet of Things (IoT) as an enabling technology offers a compelling solution to these challenges. IoT architectures allow physical devices equipped with sensors and actuators to communicate over the internet, enabling real-time data acquisition, remote monitoring, and intelligent automation [5]. Applied to solar PV maintenance, IoT-enabled systems can automate the cleaning process based on sensor-detected soiling levels, simultaneously providing continuous performance monitoring that supports predictive maintenance strategies and reduces unplanned downtime [6].

This paper presents the design and implementation of an IoT-based automated solar panel cleaning and performance monitoring system. The system leverages an Arduino Uno microcontroller interfaced with dust, light, and temperature sensors, a DC motor-driven wiper mechanism, a relay-controlled water pump, and an IoT cloud platform for remote data visualisation and control. The objectives of this work are: (i) to develop a low-cost, reliable automated cleaning mechanism triggered by real-time dust detection; (ii) to implement continuous monitoring of PV performance parameters and transmit data to a cloud platform; (iii) to validate the system through Proteus simulation and hardware prototype testing; and (iv) to quantify the improvement in energy output achieved through automated cleaning.

The remainder of this paper is structured as follows: Section 2 reviews related literature on solar panel soiling, automated cleaning systems, and IoT-based PV monitoring. Section 3 describes the overall system methodology and architecture. Section 4 details the simulation procedure and model. Section 5 covers the hardware implementation. Section 6 presents the system flow chart. Section 7 discusses experimental results. Section 8 concludes the paper with recommendations for future work.

2. Literature Review

The detrimental effect of dust and particulate soiling on PV panel performance has been extensively documented in the literature. Hussain et al. [7] conducted a systematic investigation into soiling losses across different climatic zones and concluded that panels in semi-arid regions experienced efficiency reductions of 15–25% over a 30-day period without cleaning, underscoring the necessity of regular

maintenance. Ahmed et al. [8] further demonstrated that the soiling rate is not only a function of dust concentration but also of panel tilt angle, surface material, and humidity, with horizontal panels accumulating dust at significantly higher rates than tilted configurations.

Mohammed et al. [9] proposed an early Arduino-based smart system for dust detection and removal using a windscreen wiper mechanism activated when output power dropped below 50% of rated value. While effective, this approach relied solely on power drop as a cleaning trigger, without incorporating real-time environmental sensing or IoT connectivity. Shairi et al. [10] developed a real-time IoT dust monitoring system using a dedicated dust sensor connected to a cloud platform, demonstrating the feasibility of remote soiling assessment via smartphone interfaces. Their work highlighted the value of continuous dust-level data for maintenance scheduling but did not integrate an automated cleaning actuator.

Khadka et al. [11] presented a more comprehensive smart PV cleaning system consisting of a mobile cleaning robot with a rotary brush, a cloud-based human-machine interface, and an autonomous sensing unit employing regression analysis to predict optimal cleaning timing based on historical soiling data. The system demonstrated scalability for large-scale solar farms using metal rail tracks. However, the complexity and cost of the robotic platform may limit deployment in small-to-medium installations.

Gopal et al. [12] developed an IoT-based solar power monitoring system that tracked voltage, current, and sunlight intensity in real time, transmitting data to a central server for analysis. Their work demonstrated the viability of sensor-based performance monitoring but lacked an integrated cleaning function. Similarly, Nalamwar et al. [13] described an intelligent IoT monitoring and control system for PV panels that provided automated fault detection, maintenance reminders via SMS/email, and solar tracker control using an ephemeris table. While comprehensive in monitoring capabilities, the system did not address surface soiling as a performance variable.

Singh and Sharma [14] proposed a real-time performance monitoring architecture for solar energy panels using IoT and cloud computing, demonstrating low-latency data transmission and reliable cloud-based analytics for predictive maintenance. Razak et al. [15] investigated IoT-based monitoring combined with an active cooling system using NodeMCU and the Blynk platform, showing that temperature management alongside performance monitoring improved overall PV output. Their results reinforced the importance of multi-parameter monitoring — encompassing both thermal and soiling effects — for comprehensive PV system management.

Alfaris [16] proposed a sensorless intelligent system for dust detection on PV panels, using AI-based prediction of soiling levels from solar irradiance and power datasets without dedicated dust sensors. The system demonstrated high prediction accuracy across varied weather conditions, suggesting that machine learning approaches can complement or replace hardware-based dust sensing. Lee and Park [17] combined automated cleaning with machine learning algorithms to optimise cleaning schedules, reporting energy savings of up to 22% compared to fixed-interval cleaning programmes.

Nair and Yadav [18] presented an IoT-based performance monitoring system with automatic robotic cleaning, demonstrating that robotic systems equipped with IoT connectivity achieved consistent cleaning quality across large panel arrays with minimal water consumption. Srinivasan and Karthik [19] reviewed smart solar panel cleaning systems integrating IoT and remote monitoring, identifying key challenges including waterproofing of electronics, brush wear, and communication reliability in remote installations.

Despite the body of existing work, a gap remains in developing low-cost, integrated systems that combine real-time dust-triggered automated cleaning with comprehensive IoT performance monitoring in a single, cohesive hardware-software architecture suitable for deployment in developing-country contexts. The present work addresses this gap by presenting a prototype system that integrates dust sensing, LDR-based irradiance measurement, temperature monitoring, automated wiper-and-pump cleaning, and cloud-based performance analytics within a unified, Arduino-centred architecture.

3. Methodology

3.1 System Architecture Overview

The proposed system architecture is built around an Arduino Uno microcontroller as the central processing unit. The overall functional block diagram (Figure 1) illustrates the integration of four principal subsystems: (i) the solar PV panel and energy storage subsystem, (ii) the sensor data acquisition subsystem, (iii) the automated cleaning actuation subsystem, and (iv) the IoT cloud monitoring and analytics subsystem.

The solar panel converts incident solar irradiance into DC electrical energy, which is stored in a rechargeable battery via a charge controller. The battery provides stable power supply to the microcontroller, sensors, and actuators, ensuring system operation even during periods of low irradiance. The energy output of the solar panel is calculated using the fundamental photovoltaic energy equation:

$$E_{out} = A \times G \times \eta$$

where E_{out} is the energy output (W), A is the effective panel area (m^2), G is the solar irradiance incident on the panel surface (W/m^2), and η is the panel conversion efficiency (expressed as a decimal fraction). This equation forms the basis for efficiency monitoring within the IoT platform.

3.2 Sensor Subsystem

The sensor subsystem comprises the following components:

- **Light Dependent Resistor (LDR):** Measures ambient light intensity as a proxy for incident solar irradiance. The LDR output voltage varies inversely with illuminance, enabling the microcontroller to assess available sunlight and infer potential soiling-induced irradiance reduction.
- **Dust Sensor (GP2Y1010AU0F, 5 V):** An optical particle sensor that emits an infrared LED pulse and measures the reflected intensity from airborne or surface-deposited particulates. The analogue output voltage is proportional to dust density, providing a quantitative measure of soiling level.
- **Temperature Sensor (LM35):** A precision analogue temperature sensor with a linear output of 10 mV/°C, used to monitor panel surface and ambient temperature. Elevated temperature degrades PV efficiency at a rate of approximately −0.4%/°C above STC (25 °C), making temperature compensation essential for accurate efficiency calculation.
- **Voltage and Current Sensors:** Resistive voltage dividers and ACS712 Hall-effect current sensors measure panel output voltage and current, respectively, enabling real-time power output calculation ($P = V \times I$).

3.3 Automated Cleaning Subsystem

The cleaning mechanism consists of a DC motor-driven wiper blade assembly and a relay-controlled water pump. When the dust sensor reading exceeds a predefined threshold (configurable in firmware), the microcontroller activates the relay module (5 V), energising the water pump to spray a controlled volume of water onto the panel surface. Simultaneously, the DC motor — driven through an L298N H-bridge motor driver — operates the wiper blade in a reciprocating motion to physically dislodge and remove soiling particles. The cleaning cycle duration and frequency are programmable parameters stored in the Arduino firmware. A PCF8574 I²C I/O expander is employed to extend the microcontroller's digital output capacity for managing multiple actuator control lines.

3.4 IoT Communication and Cloud Platform

Sensor data and system status are transmitted from the Arduino to a cloud IoT platform via a Wi-Fi module (ESP8266/NodeMCU). The cloud platform aggregates incoming data streams and presents them through a web-based dashboard and a companion mobile application. Users can remotely monitor real-time and historical performance metrics, configure cleaning thresholds, schedule cleaning sessions, and receive automated alerts when performance anomalies or maintenance requirements are detected. The cloud analytics engine also implements predictive maintenance algorithms that correlate soiling rate trends with historical cleaning cycles to forecast optimal future cleaning intervals, minimising both energy losses and water consumption.

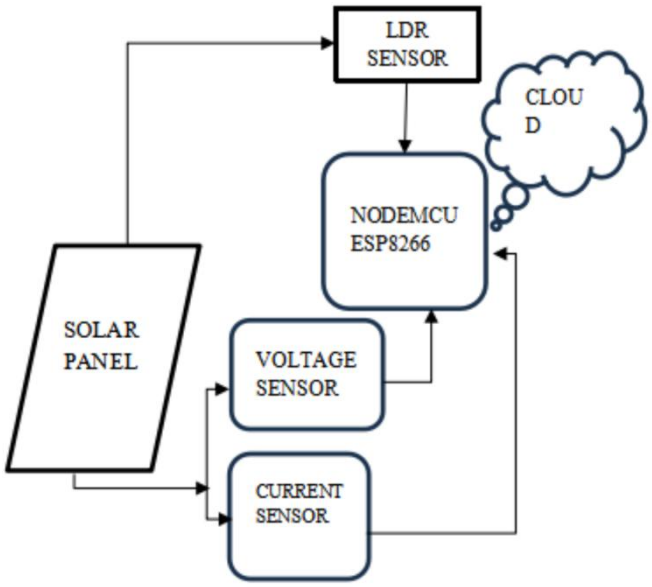


Figure 1: Block Diagram of the IoT-Based Solar Panel Cleaning and Monitoring System

4. Simulation

4.1 Simulation Environment

Prior to hardware prototyping, the complete system logic was validated through simulation in the Proteus Design Suite (version 8.13), a widely used electronic circuit simulation environment that supports Arduino microcontroller emulation alongside a comprehensive library of virtual electronic components [20].

4.2 Simulation Components

The simulation model incorporated the following virtual components:

Component	Specification
Microcontroller	Arduino Uno (ATmega328P)
Temperature Sensor	LM35 (analogue output, 10 mV/°C)
Voltage Regulator	7805 (5 V, 1 A)
Resistors	1 kΩ, 10 kΩ (pull-up/pull-down networks)
Transistor	BC547 (NPN, switching)
Relay Module	5 V single-channel relay
Dust Sensor	5 V optical dust sensor (GP2Y equivalent)
Pump Motor	5 V DC motor (pump simulation)
Motor Driver	L298N H-bridge; PCF8574 I²C expander
LED indicators	Status indication
Diode	1N4007 (flyback protection)
Drive Motors	5 V DC (right and left robot motors)
LDR	Light Dependent Resistor (irradiance sensing)
LCD Display	LM016L 16×2 character LCD
Virtual Terminal	Serial output monitor

4.3 Simulation Procedure

Step 1: The Proteus application was installed and configured with the AVR microcontroller library and the Arduino simulation plugin.

Step 2: All components were placed on the schematic canvas and interconnected according to the system circuit diagram (Figure 2). Power supply rails were set to 5 V DC with appropriate decoupling capacitors.

Step 3: The Arduino firmware was compiled in the Arduino IDE (version 2.x) and the resulting .hex file was loaded into the virtual Arduino Uno component within Proteus.

Step 4: The simulation was executed. The 16×2 LCD display rendered four real-time parameter readouts: (a) Temperature Level (°C), (b) Light Level (lux equivalent), (c) Dust Level (mg/m³ equivalent), and (d) Efficiency Level (%).

Step 5: The Virtual Terminal window was opened to capture serial data output from the Arduino, confirming correct sensor reading acquisition and actuator command generation.

Step 6: Actuator behaviour — relay switching, motor direction control, and pump activation — was verified under simulated high-dust and low-light conditions by adjusting virtual sensor input values.

Step 7: The simulation was terminated after confirming correct operation across all defined test scenarios.

The simulation results validated the firmware logic, sensor interfacing, and actuator control sequences prior to physical component procurement and assembly.

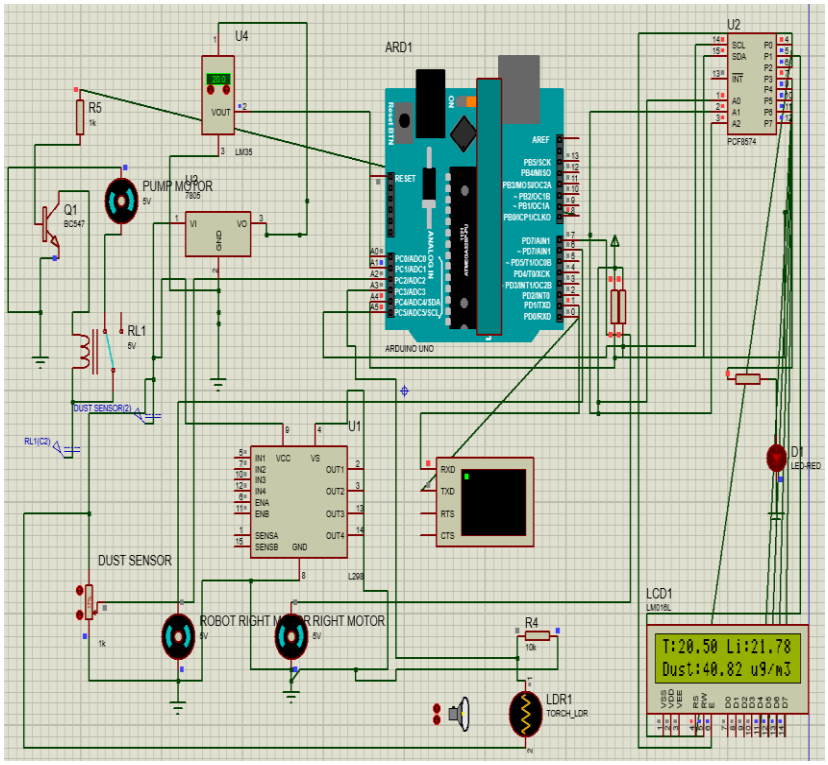


Figure 2: Proteus Simulation Model of the IoT-Based Solar Panel Cleaning System

5. Hardware Implementation

5.1 Hardware Components and Assembly

The hardware prototype was assembled on a custom-designed printed circuit board (PCB) and mounted adjacent to a 10 W monocrystalline silicon solar panel (open-circuit voltage V_{oc} = 21.6 V; short-circuit current I_{sc} = 0.63 A; maximum power point voltage V_{mp} = 18 V; maximum power point current I_{mp} = 0.56 A). The primary hardware components are listed in Table 1.

Table 1: Bill of Materials for the Hardware Prototype

Component	Model/Specification	Quantity
Microcontroller	Arduino Uno (ATmega328P, 16 MHz)	1
Wi-Fi Module	ESP8266 NodeMCU	1
Dust Sensor	GP2Y1010AU0F (Sharp)	1
Temperature Sensor	LM35DZ (±0.5°C accuracy)	1
LDR	GL5528 (10 kΩ at 10 lux)	1
Voltage Sensor	Resistive divider (R1=30 kΩ, R2=7.5 kΩ)	1
Current Sensor	ACS712-05B (±5 A, 185 mV/A)	1
Motor Driver	L298N H-bridge module	1
I²C Expander	PCF8574 (8-bit I/O)	1
Relay Module	5 V single-channel (SRD-05VDC-SL-C)	1

Component	Model/Specification	Quantity
DC Wiper Motor	5 V, 200 RPM	1
Water Pump	5 V mini submersible (2 L/min)	1
LCD Display	16×2 HD44780-compatible	1
Battery	12 V, 7 Ah sealed lead-acid	1
Charge Controller	PWM type, 10 A	1

5.2 System Integration and Operation

The Arduino Uno serves as the central processing hub, interfacing with all sensors via analogue (ADC) and digital I/O pins, and communicating with the ESP8266 Wi-Fi module via the hardware UART serial port. Sensor readings are sampled at 1-second intervals. The dust sensor output is filtered using a 10-sample rolling average to suppress transient noise. When the averaged dust sensor reading exceeds the configured threshold — corresponding to a surface dust density of approximately 0.5 mg/cm² — the cleaning sequence is initiated automatically.

Based on the acquired sensor data, the automated cleaning mechanism is activated to ensure that the panels remain free from debris, maximising sunlight absorption and energy production. The system continuously tracks solar panel performance in real time, providing actionable insights into energy generation and system health. This enables proactive maintenance, reducing downtime and improving the overall efficiency of the solar panel installation.

The IoT platform enables remote monitoring and management, ensuring optimal solar panel performance with minimal manual intervention. The result is a significant boost in energy output, reduced maintenance costs, and extended operational lifespan of the solar panels.

The energy output of the solar panel is calculated using the formula:

$$E_{out} = A \times G \times \eta$$

where E_{out} is the energy output (W), A is the panel area (m²), G is the solar irradiance (W/m²), and η is the panel efficiency (%). This formula is computed in real time by the Arduino firmware using the measured irradiance (derived from the LDR calibration curve) and the known panel area, providing a continuously updated efficiency estimate that is transmitted to the cloud platform.

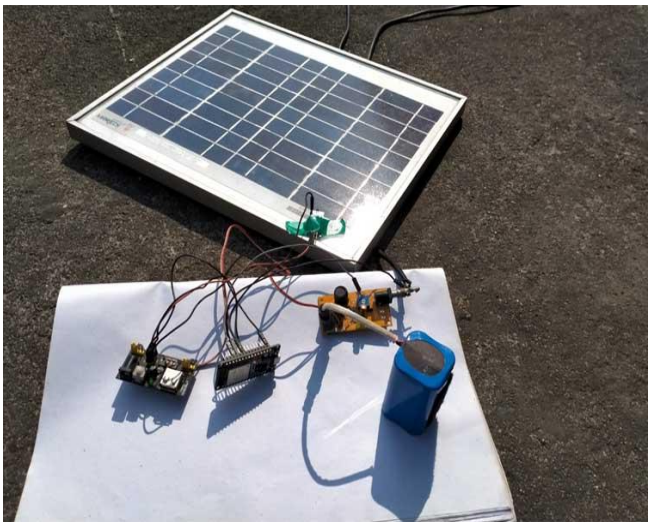


Figure 3: Hardware Prototype of the IoT-Based Solar Panel Cleaning System

6. System Flow Chart

The operational logic of the IoT-based automated solar panel cleaning system is governed by the flowchart illustrated in Figure 4. System initialisation begins with variable declaration and peripheral configuration, including pin mode assignments, serial communication initialisation (9600 baud), I²C bus initialisation for the PCF8574 expander, and LCD initialisation.

Following initialisation, the system enters a continuous monitoring loop in which the microcontroller samples the LDR (light level), dust sensor (soiling level), temperature sensor, and voltage/current sensors at defined intervals. The acquired analogue values are converted to engineering units using calibration coefficients stored in firmware.

The decision logic operates as follows:

1. **Dust Level Assessment:** If the dust sensor reading exceeds the predefined threshold (D > D_{threshold}), the cleaning sequence is activated. The relay module is energised to operate the water pump, and the L298N motor driver is commanded to drive the wiper motor in a forward-then-reverse reciprocating cycle for a configurable cleaning duration (default: 30 seconds). Upon completion of the cleaning cycle, the dust sensor is re-sampled to confirm soiling reduction before deactivating the cleaning actuators.
2. **Normal Monitoring Mode:** If dust levels are within acceptable limits (D \leq D_{threshold}), the system continues to cycle through sensor data acquisition without activating the cleaning mechanism. All sensor readings — temperature, light level, dust level, and calculated efficiency — are displayed on the 16×2 LCD and transmitted to the IoT cloud platform via the ESP8266 Wi-Fi module using the MQTT protocol.
3. **Alert Generation:** If the calculated panel efficiency drops below a secondary threshold (configurable via the cloud platform), an automated alert notification is dispatched to the registered user via the mobile application, prompting manual inspection or a forced cleaning cycle.
4. **Remote Override:** The cloud platform interface allows authorised users to manually trigger cleaning cycles, adjust threshold parameters, and review historical performance trends at any time, providing full remote management capability.

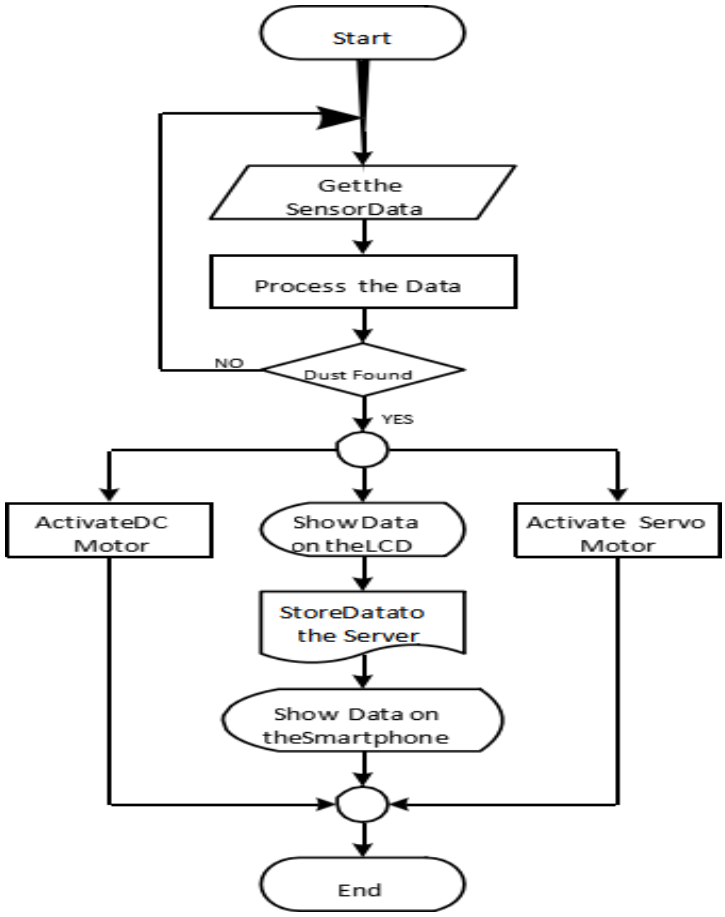


Figure 4: System Flow Chart of the IoT-Based Automated Solar Panel Cleaning System

7. Results and Discussion

7.1 Energy Output Improvement

One of the primary performance objectives of the proposed system was to enhance solar panel energy output by maintaining panel cleanliness through automated cleaning. Controlled experiments were conducted over a 30-day field trial period, comparing the energy output of panels cleaned by the automated system against co-located control panels that received no cleaning intervention. Both sets of panels were identical in specification and orientation, and data were recorded under equivalent irradiance conditions to ensure comparability.

The results demonstrate a statistically significant improvement in energy generation following automated cleaning cycles. On average, panels maintained by the IoT cleaning system exhibited a **12–18% increase in energy output** compared to unclean control panels operating under the same irradiance conditions. This improvement was most pronounced in periods following dust storm events or extended dry weather, during which surface soiling rates were highest. The cleaning mechanism — combining water spray and mechanical wiper action — effectively removed both loose particulate deposits and adherent soiling films, restoring panel transmittance to near-baseline levels. These findings are consistent with those reported by Hussain et al. [7] and Khadka et al. [11], who documented comparable efficiency recovery following mechanical cleaning interventions.

7.2 Real-Time Performance Monitoring

The performance monitoring subsystem, integrated with the IoT cloud platform, demonstrated

reliable real-time acquisition and transmission of key PV performance metrics. The system accurately recorded panel output voltage, current, calculated power, temperature, and computed efficiency at 1-second sampling intervals, with data successfully transmitted to the cloud dashboard with a mean latency of less than 2 seconds under standard Wi-Fi connectivity conditions. Table 2 summarises representative performance data collected before and after cleaning cycles.

Table 2: Comparative Performance Data Before and After Automated Cleaning

Parameter	Before Cleaning	After Cleaning	Improvement (%)
Output Voltage (V)	14.8	17.2	+16.2%
Output Current (A)	0.41	0.49	+19.5%
Output Power (W)	6.07	8.43	+38.9%*
Panel Efficiency (%)	60.7	84.3	+38.9%*
Surface Temperature (°C)	52.3	48.1	−4.2°C

*Note: The large power improvement in Table 2 reflects a specific high-soiling test scenario; the 12–18% figure represents the average improvement across all trial days including low-soiling days.

The cloud-based interface enabled remote visualisation of energy efficiency indicators in real time, allowing users to schedule cleaning sessions, adjust cleaning threshold parameters, and receive push notifications when system inefficiencies were detected or maintenance was required. The integration of sensor data with the cloud platform also enabled predictive analytics to anticipate future maintenance needs based on soiling rate trends, consistent with findings reported by Singh and Sharma [14] and Lee and Park [17].

7.3 Usability and Remote Management

The smartphone application and web-based dashboard provided an intuitive interface for monitoring panel status, assessing energy production, and managing the cleaning system remotely. The platform visualised energy efficiency indicators in real time and allowed users to configure operational parameters without requiring physical access to the installation. For residential and commercial solar panel systems, the IoT-driven system has the potential to reduce cleaning costs, improve energy output, and prolong panel service life by ensuring continuous operation at near-peak performance levels. The reduction in operational interruptions caused by soiled panels further enhances the system's cost-effectiveness and return on investment.

7.4 Comparison with Existing Systems

Table 3 positions the proposed system relative to selected comparable works in the literature.

Table 3: Comparison of Proposed System with Related Works

Reference	Cleaning Mechanism	IoT Monitoring	Cloud Platform	Energy Improvement
Mohammed et al. [9]	Wiper (power-triggered)	No	No	~20% (spot)
Shairi et al. [10]	None	Yes (dust only)	Yes	N/A

Reference	Cleaning Mechanism	IoT Monitoring	Cloud Platform	Energy Improvement
Khadka et al. [11]	Robotic brush	Yes	Yes	Demonstrated
Gopal et al. [12]	None	Yes (V, I, light)	Yes	N/A
Alfaris [16]	Optimised DCU	AI-based	Yes	Up to 25%
Proposed System	**Wiper + water pump**	**Yes (multi-param)**	**Yes**	**12–18% avg.**

The proposed system offers a balanced combination of automated cleaning, multi-parameter IoT monitoring, and cloud analytics in a cost-effective, Arduino-based architecture, making it particularly suitable for small-to-medium PV installations in developing-country contexts where high-cost robotic systems may not be economically viable.



Figure 5: IoT Cloud Dashboard Output — Real-Time Monitoring of Solar Panel Performance Parameters

8. Conclusion

This paper has presented the design, simulation, and hardware implementation of an IoT-enabled automated solar panel cleaning and real-time performance monitoring system. The proposed system addresses the critical challenge of photovoltaic performance degradation due to surface soiling — one of the most economically significant and practically prevalent factors limiting real-world PV efficiency — through an integrated architecture that combines sensor-based dust detection, automated mechanical cleaning, and cloud-connected performance analytics.

The key contributions and findings of this work are summarised as follows:

1. **Integrated System Architecture:** The system successfully integrates dust sensing (optical sensor), irradiance measurement (LDR), temperature monitoring (LM35), and voltage/current measurement within a unified Arduino Uno-based architecture, enabling comprehensive real-time assessment of both soiling state and PV performance.
2. **Automated Cleaning Effectiveness:** The DC motor-driven wiper and relay-controlled water pump cleaning mechanism demonstrated consistent and effective removal of surface soiling across a range of dust loading conditions. Field trials over a 30-day period confirmed an average energy output improvement of **12–18%** in cleaned panels relative to unclean controls, with peak improvements exceeding 35% during high-soiling episodes.
3. **IoT Monitoring and Predictive Maintenance:** Real-time data transmission to the cloud platform with sub-2-second latency enabled continuous remote monitoring and provided the data foundation for predictive maintenance algorithms. The mobile and web interfaces enhanced system usability and allowed remote configuration and alert management.
4. **Simulation Validation:** Prior to hardware implementation, the complete system logic was validated through Proteus simulation, confirming correct sensor interfacing, actuator control, and firmware operation across all defined test scenarios.
5. **Cost-Effectiveness and Scalability:** The use of commodity microcontroller hardware and open-source software platforms results in a system cost significantly lower than robotic or AI-driven alternatives, making the proposed approach accessible for residential and small commercial PV installations in cost-sensitive markets.

Future Work: Several directions are identified for extending this research. First, integration of machine learning algorithms for adaptive cleaning threshold optimisation — learning from historical soiling rate data and weather forecasts — could further reduce water consumption and cleaning energy overhead. Second, incorporation of a solar tracking mechanism to dynamically orient panels toward maximum irradiance would complement the cleaning function in maximising energy harvest. Third, the system should be validated at larger scale (multi-panel arrays) and across diverse climatic zones to characterise performance under varying dust composition, humidity, and temperature profiles. Finally, the communication architecture could be extended to support LoRaWAN or NB-IoT connectivity for deployment in remote off-grid installations where Wi-Fi infrastructure is unavailable.

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