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Performance Enhancement of Solar PV Panels Using Splash Fill Cooling under Tropical Conditions

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Abstract

This study examines the effectiveness of a splash fill cooling system in reducing the temperature of solar photovoltaic (PV) modules and enhancing their electrical performance under tropical conditions. Two identical 50 Wp PV modules were tested in parallel, with one equipped with the splash fill cooling system and the other serving as a reference without cooling. The cooling system was controlled by an Arduino Uno using threshold-based logic, which activated a water pump when the panel temperature exceeded 40°C. Real-time monitoring of temperature, voltage, and current was conducted over seven consecutive days (July 1–7, 2025). Results showed that splash fill cooling reduced panel temperature by an average of 4–5°C compared to the reference module. This reduction led to an increase in output current (2.7–3.3%) and power (2.7–4.3%), while voltage improvement remained modest at around 0.9%. Regression analysis revealed a strong negative correlation ($R^2 > 0.85$) between temperature and power output, confirming temperature as a dominant factor in PV efficiency. The findings highlight splash fill cooling as a simple, cost-effective, and water-efficient solution for improving PV performance in tropical climates, offering practical implications for small-scale and off-grid solar applications.

Keywords

Solar photovoltaic, splash fill cooling, tropical climate, Arduino-based control, Energy efficiency

Introduction

Photovoltaic (PV) technology has become a cornerstone of the global transition to renewable energy, driven by the need for clean and sustainable power sources. However, the performance of PV modules is highly sensitive to operating temperatures. For crystalline silicon modules, each degree Celsius above 25 °C results in an efficiency drop of approximately –0.4% to –0.5% per °C, which poses a significant challenge in tropical climates where surface temperatures frequently

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exceed 45 °C. This condition not only reduces energy output but also accelerates material degradation (Li et al., 2025).

To address these thermal limitations, various PV cooling strategies have been investigated, including passive (e.g., heat sinks, phase change materials, radiative cooling), active (e.g., spray cooling, forced convection, microchannels, photovoltaic/thermal hybrids), and hybrid systems. In recent years (2020–2025), there has been a marked focus on evaporative cooling methods, which utilize water films or sprays to lower panel surface temperature and enhance overall electrical efficiency (Mao et al., 2025; Naqvi et al., 2024).

Recent literature confirms the effectiveness of evaporative cooling in boosting PV performance under high-temperature conditions. Harmailil et al. (2024) and Utomo et al. (2025) provide systematic reviews of water-based cooling techniques, particularly backside spray methods, which have been shown to improve monthly energy yields, especially for rooftop PV installations in tropical regions. Similarly, Bayrak et al. (2025) and Li et al. (2025) highlight the benefits of optimized spray cooling designs that significantly reduce surface temperature and increase electrical power output.

Advanced innovations such as the self-adaptive wicking evaporator (SWE) system, proposed by Li et al. (2025), offer intelligent passive temperature regulation through capillarity and adaptive electronics. Although promising, such systems remain complex and costly for small-scale applications. Naqvi et al. (2024) and Ahmed et al. (2024) validate the performance of water-mist cooling systems, which effectively reduce operational temperature and thermal stress with minimal energy consumption.

Moreover, studies by Haidar et al. (2020) and Basem et al. (2024) indicate that splash fill cooling systems present a simple and cost-effective alternative, achieving up to 20% increases in electrical efficiency in real-world tropical environments. This finding is reinforced by Li et al. (2025), who explored front-side water spray systems that offer practical cooling solutions for small-scale PV installations due to their low cost and easy implementation. Mao et al. (2025) further evaluated the techno-economic viability of spray cooling systems in hot-humid regions, while Naqvi et al. (2024) confirmed the effectiveness of mist nozzle systems in increasing power output. Bamisile et al. (2025) and Yaman et al. (2025) emphasize that ambient temperature is a dominant factor affecting PV output, further justifying the integration of cooling systems. Finally, Harmailil et al. (2024) provide an updated classification of PV cooling methods and assessment approaches, reinforcing the importance of simple, water-efficient, and scalable solutions.

Despite these advances, a significant research gap remains. Most studies focus on thermal performance alone and lack real-time control integration using low-cost microcontrollers such as Arduino Uno. Moreover, only a few works address trade-offs between temperature reduction, power gain, and resource consumption in low-cost, replicable splash fill systems under real tropical conditions. The current study aims to fill this gap by developing and testing an Arduino-based splash fill cooling prototype using threshold-based control and quantifying its effects on PV temperature, voltage, current, and power output under field conditions.

Methodology

This study employed a comparative experimental approach to evaluate the effectiveness of a splash fill cooling system in enhancing the performance of photovoltaic (PV) panels under tropical conditions. Two identical 50 Wp polycrystalline PV modules were installed side by side at a tilt angle of 15° and oriented southward, which is optimal for equatorial regions such as Lhokseumawe, Aceh, Indonesia. This arrangement ensured uniform exposure to solar irradiance and environmental conditions, including ambient temperature, relative humidity, and wind speed. One PV module was integrated with the splash fill cooling system, while the other served as an uncooled reference. Field experiments were conducted over seven consecutive days (July 1–7, 2025), with data collection focused on peak solar irradiance periods between 11:30 and 12:30 local time.

The splash fill cooling system comprised a 12 V DC submersible pump with a flow rate of 2.5 L/min, a perforated aluminum splash tray positioned 8 cm above the PV surface, and a closed-loop water circulation system utilizing a 15 L reservoir. Water was pumped from the reservoir and evenly distributed across the PV surface through the splash fill tray before being collected and recirculated. This configuration limited water consumption to approximately 0.3 L per cooling cycle. The system was designed to emulate passive heat exchange mechanisms commonly applied in cooling towers, thereby enhancing heat dissipation through evaporative cooling without the use of pressurized spray systems.

System automation and data acquisition were managed using an Arduino Uno microcontroller as the central control unit. Real-time PV surface temperature was measured using waterproof DS18B20 digital temperature sensors with an accuracy of ±0.5°C. Electrical parameters, including output voltage and current, were monitored using INA219 high-side current and voltage sensors with an accuracy of ±1%. The instantaneous power output was calculated onboard using $P = V \times I$. All measured and computed data were recorded to an SD card at one-minute intervals for subsequent analysis.

A relay-based control strategy was implemented to regulate cooling pump operation. The pump was activated when the PV surface temperature reached or exceeded 40°C and deactivated when the temperature dropped below 38°C. This 2°C hysteresis band was intentionally applied to prevent rapid relay switching (chattering) and to extend relay service life. Additionally, a 30 s stabilization delay was introduced after each pump state transition to allow thermal equilibration prior to subsequent data acquisition. The threshold-based control algorithm, illustrated in Figure 1, optimized energy consumption, minimized water usage, and ensured effective thermal management using low-cost hardware components.

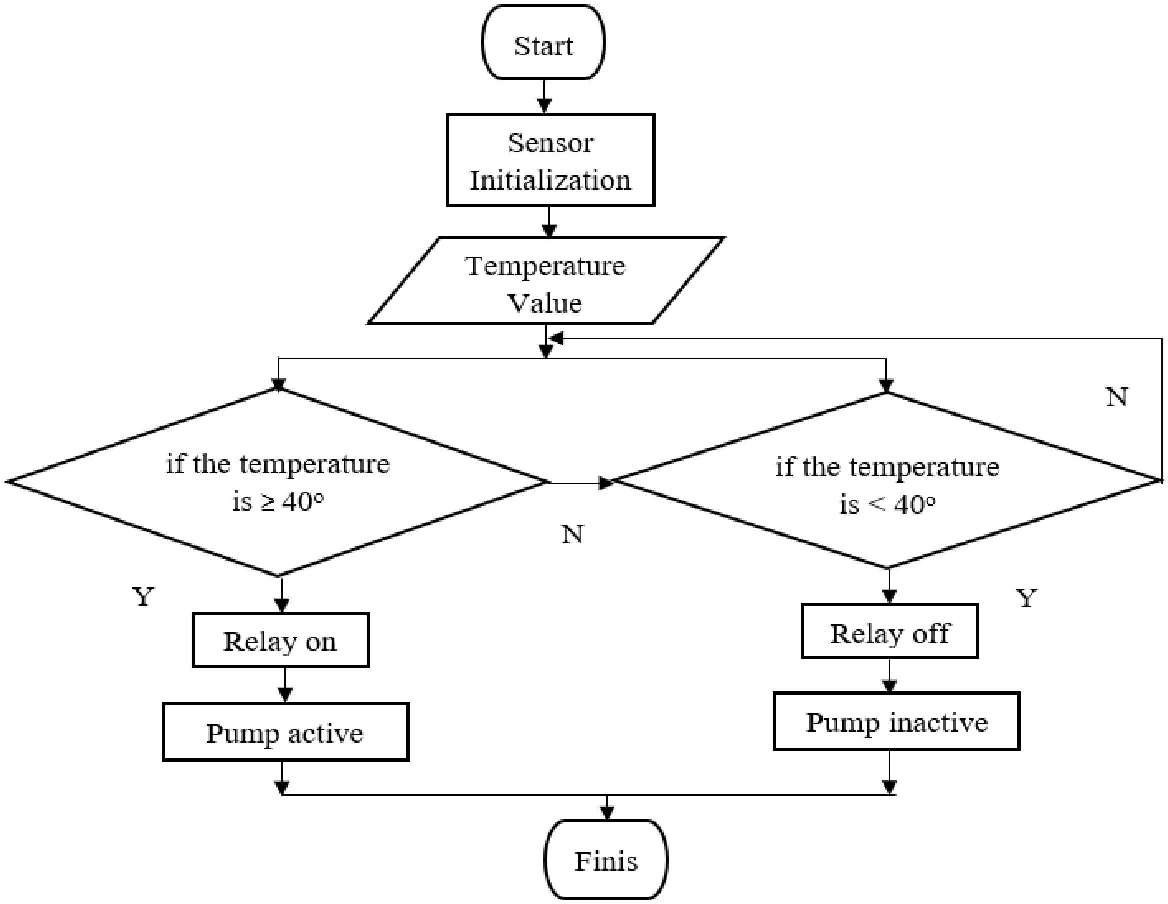

Figure 1. Control Flowchart

For autonomous operation, the entire system, including the Arduino controller, sensors, and cooling pump, was powered by a 12 V, 20 Ah battery charged by the PV modules through a PWM charge controller. This configuration rendered the system fully self-sustaining and suitable for off-grid applications. The mechanical support frame held both PV modules at the prescribed tilt angle and housed the water reservoir, pump, and piping system beneath the panels, thereby minimizing shading effects on the active PV surface.

Figure 2(a) presents the mechanical layout, illustrating the spatial arrangement of the PV modules, splash fill tray, water reservoir, and supporting structure. Figure 2(b) shows the electrical wiring diagram, detailing the integration of the Arduino Uno, DS18B20 sensors, INA219 modules, relay unit, and power supply system. The recorded parameters included PV surface temperature, open-circuit voltage, short-circuit current, and instantaneous power output. All measurements were conducted during peak solar irradiance hours (11:30–12:30 local time) to accurately assess cooling effectiveness and power enhancement under maximum thermal stress conditions.

Overall, the proposed methodology is consistent with recent studies on adaptive photovoltaic cooling techniques and demonstrates high replicability and practical feasibility for small-scale deployments in tropical regions, particularly for off-grid rural electrification applications.

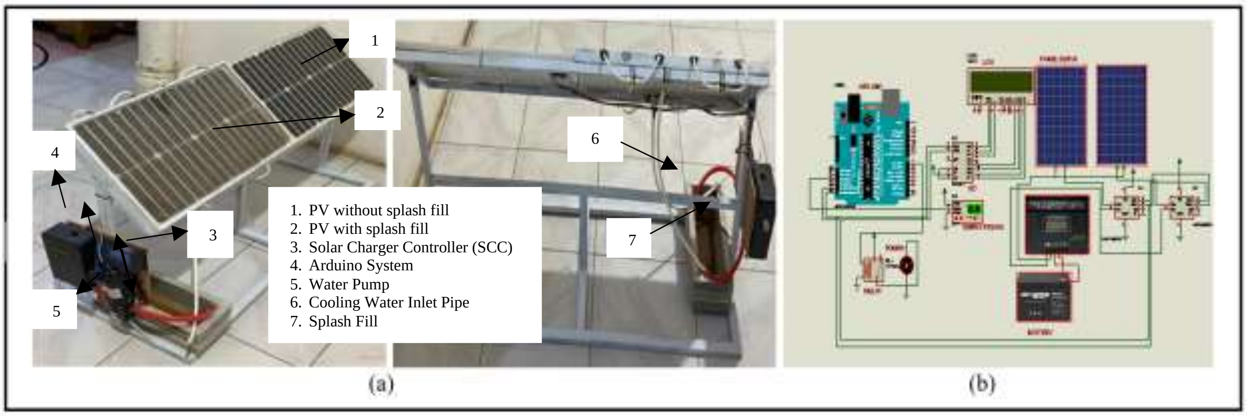

Figure 2. (a) Mechanical Design (b) Electrical Design

Results and Discussion

During the seven-day experimental period (July 1–7, 2025), the splash fill cooling system demonstrated consistent effectiveness in reducing the surface temperature of the photovoltaic (PV) panels and improving their electrical performance. As illustrated in Figure 3, the cooled PV modulemaintained surface temperatures approximately 4–5 °C lower than the uncooled reference, operating within a range of 38–40 °C compared to 42–44 °C for the uncooled panel. This temperature reduction resulted in a measurable enhancement in power output, with daily improvements ranging from 2.7% to 4.3%.

The observed variation in power improvement across the testing days is attributed to fluctuations in ambient conditions, particularly solar irradiance intensity and initial panel temperature during peak operation hours. On days with higher irradiance and elevated baseline temperatures, the cooling system exhibited a more pronounced impact, yielding power gains closer to the upper bound of the reported range. Conversely, under relatively moderate thermal conditions, the cooling effect remained beneficial but resulted in smaller efficiency gains. This trend confirms that the effectiveness of thermal management is strongly dependent on the magnitude of thermal stress experienced by the PV module.

Regression analysis further revealed a strong negative linear relationship between PV surface temperature and power output, with coefficients of determination exceeding 0.85 ($R^2 > 0.85$). This finding reinforces the critical role of temperature control in maintaining PV efficiency under tropical operating conditions.

From an electrical performance perspective, the most significant improvement was observed in output current, which increased by 2.7–3.3% on a daily basis in the cooled panel relative to the reference module. In contrast, output voltage exhibited only a marginal increase of approximately 0.8–1.0%. As shown in Figure 4, both power and current display clear negative correlations with increasing temperature, whereas voltage remains comparatively stable. This behavior is consistent with the fundamental characteristics of crystalline silicon PV modules, in which current is more sensitive to temperature variations than voltage.

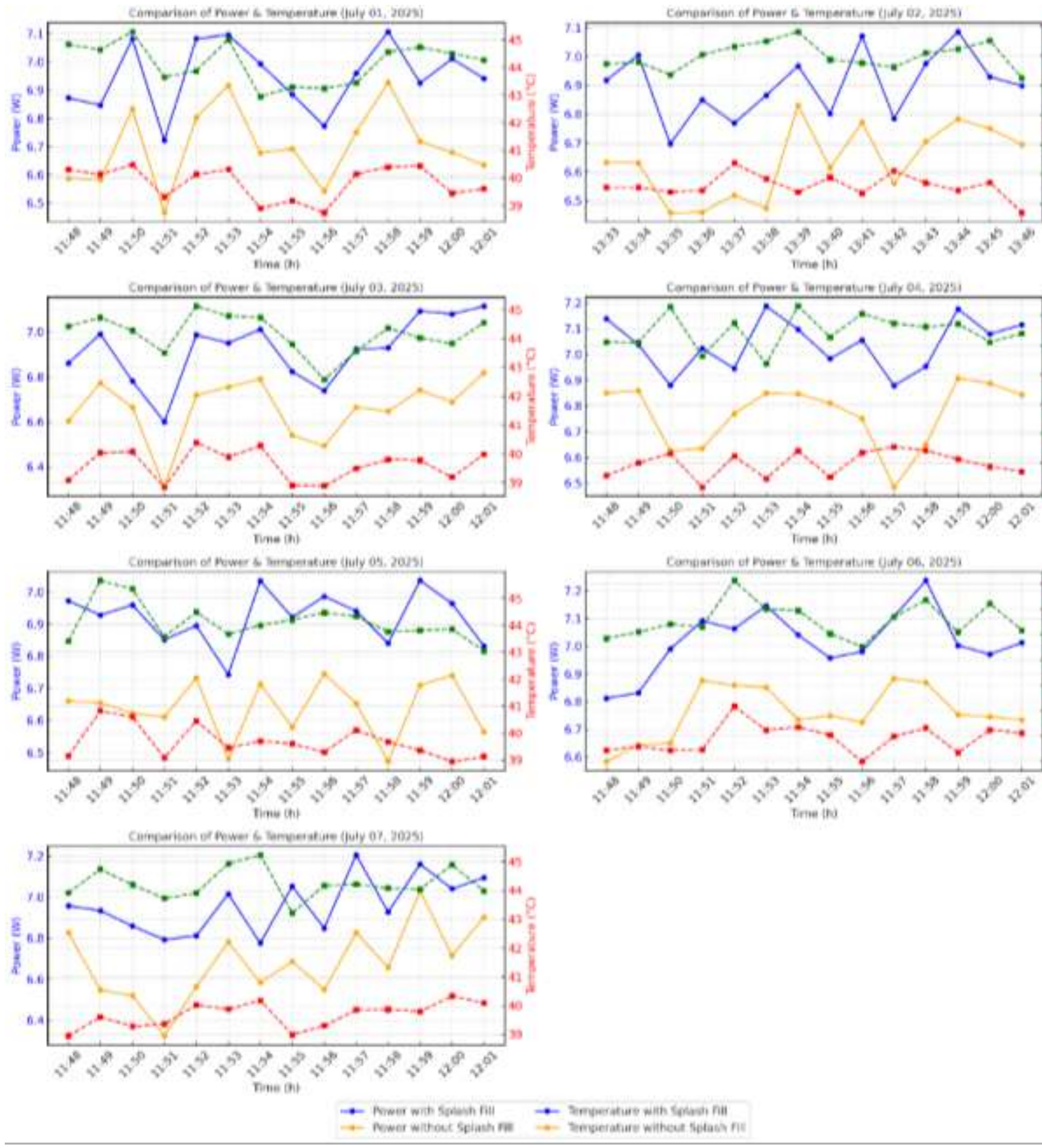

Figure 3. Comparison of Power and Temperature Trends

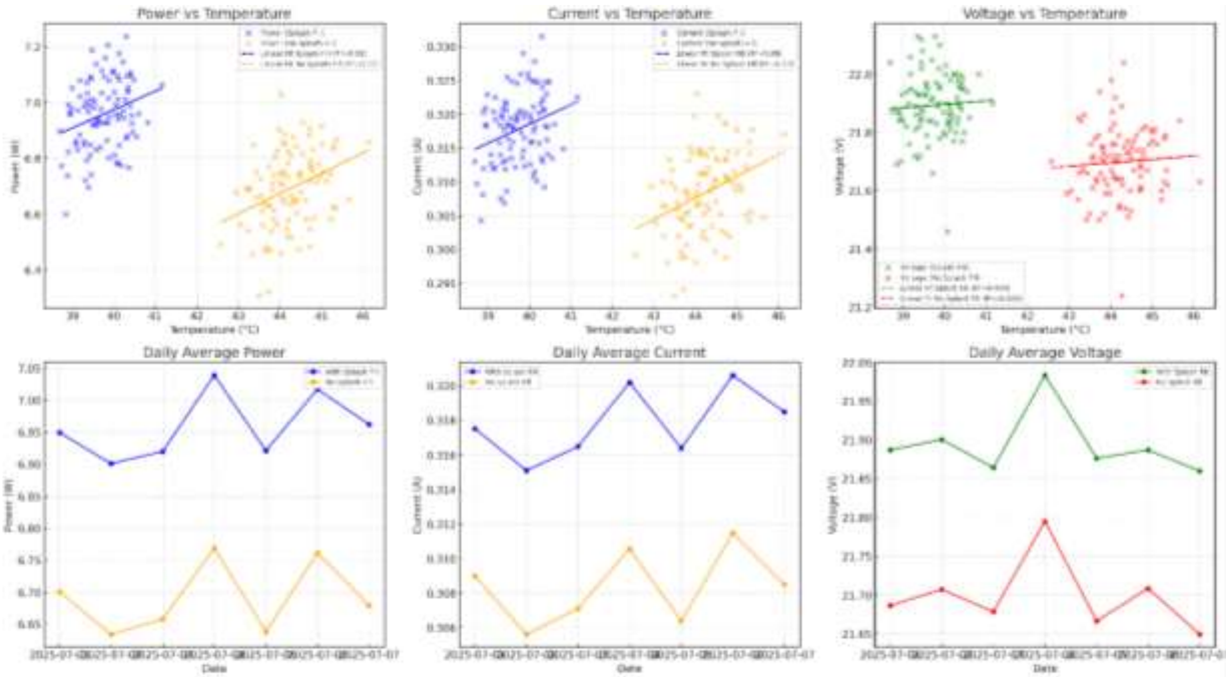

Figure 4. Linear Regression Analysis of Power, Current, and Voltage vs. Temperature

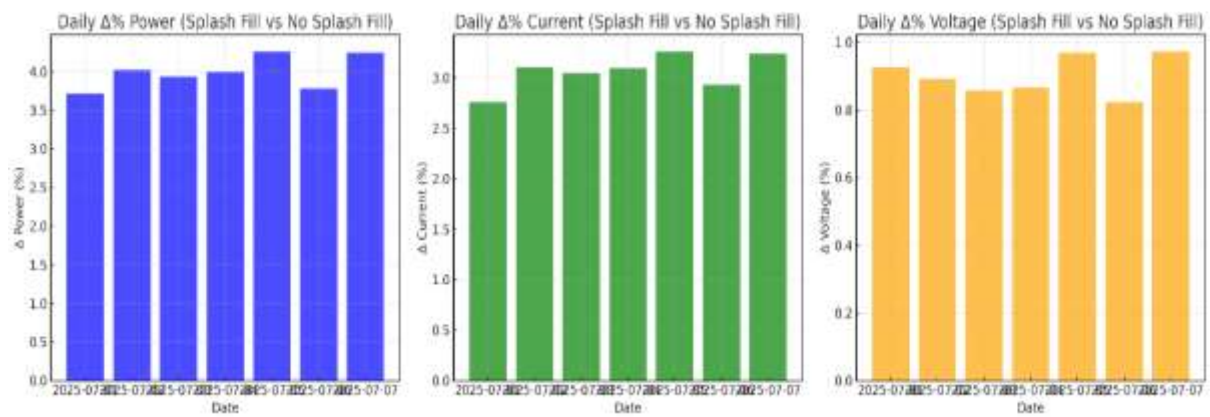

Figure 5. Daily Percentage Improvement Power, Current and Voltage

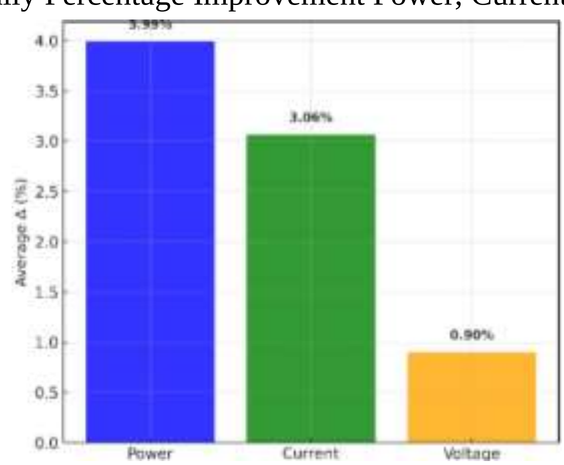

Figure 6. Average Percentage Improvement

Figures 5 and 6 present the daily and average percentage improvements, respectively. Over the entire testing period, the splash fill cooling system achieved average enhancements of 4.0% in power output, 3.1% in current, and 0.9% in voltage. These improvements were obtained using a simple closed-loop water cooling mechanism with minimal water consumption, highlighting the practicality and resource efficiency of the proposed approach for small-scale PV installations in tropical environments.

When compared with existing literature, the efficiency gains achieved using the splash fill technique are relatively modest. Advanced cooling strategies such as pressurized water spraying, dew-point cooling, or phase-change material (PCM)-based systems have been reported to deliver performance improvements exceeding 7–8% (Haidar et al., 2020; Mohammed Noori Mahmood & Ali Aljubury Assist, 2023; Sunu et al., 2024; Yang et al., 2024). However, these approaches typically involve more complex system architectures, higher energy consumption, or increased water usage, which may limit their feasibility for small-scale or off-grid applications.

In contrast, the splash fill cooling method offers a simplified and low-cost alternative, operating with low water flow rates, non-pressurized distribution, and minimal auxiliary energy requirements. Its advantages lie in operational simplicity, reduced maintenance demands, and efficient resource utilization. These attributes align with recent techno-economic assessments emphasizing that the sustainability of PV cooling solutions should consider not only thermal performance but also system complexity, water consumption, and long-term viability (Harmailil et al., 2024; Mao et al., 2025).

Therefore, although the thermal performance of splash fill may be lower than advanced methods, its practicality and environmental suitability make it a viable solution, especially for residential or off-grid deployments in tropical climates characterized by high solar irradiance and thermal stress.

Conclusion

The splash fill cooling system successfully reduced PV module temperatures by an average of 4–5°C, resulting in 2.7–4.3% higher power output compared to uncooled panels. Regression analysis ($R^2 > 0.85$) confirmed temperature as the dominant factor affecting efficiency. These findings demonstrate splash fill as a practical, low-cost, and water-efficient cooling strategy for PV applications in tropical climates.

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