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Cybersecurity Framework for Smart Atmospheric Water Harvesting Systems Powered by Renewable Energy

Dr. P Radha
Professor
School of Commerce, JAIN (Deemed–to–be University), Bengaluru, India
pradha1020@gmail.com
https://orcid.org/0000-0001-8172-8471

Dr. B. Senthil Kumar
Assistant Professor
Jain CMS Business School, Bengaluru, India
pgsentil.hr@gmail.com
https://orcid.org/0009-0002-7483-0413

S. Padmanabhan
Assistant Professor
St. Francis College, Bengaluru, India
sairampadp2181@gmail.com
https://orcid.org/0009-0008-5461-1022

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Abstract

Objective: This paper aims to address the cybersecurity vulnerabilities of smart Atmospheric Water Generators (AWGs) by proposing a secure-by-design architecture that ensures the integrity, availability, and authenticity of sensing, control, and communication processes in renewable-energy-powered water harvesting systems.

Methods: The proposed system integrates thermoelectric (Peltier) cooling with multi-stage purification (sediment filtration, activated carbon, UV sterilization) and employs image-processing-based monitoring for real-time condensation analysis, generation rate estimation, and tank-level assessment. A cybersecurity framework is embedded within the IoT–SCADA control stack, incorporating threat modeling, secure communication protocols, device identity and authentication, firmware integrity verification, role-based access control, and anomaly

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detection based on process and power telemetry. Experimental validation was conducted under varying humidity and temperature conditions, alongside simulated attack scenarios (sensor spoofing, command injection, denial-of-service) to evaluate security resilience.

Results: The system demonstrated reliable water production across a range of environmental conditions. Security validation showed enhanced detection and mitigation of common IoT/ICS attack vectors, with improved resilience against data manipulation and control disruptions while maintaining operational performance.

Conclusion: The integrated cyber-resilient design supports decentralized, sustainable potable water supply for rural, remote, and disaster-affected regions, offering a robust framework that combines renewable-energy operation with active security monitoring without compromising water production efficiency.

Keywords: Atmospheric Water Generator, Condensation Control, IoT Security, SCADA Security, Thermoelectric Cooling

1. Introduction

Rapid population growth, climate change, and uneven freshwater distribution have intensified global water scarcity. Conventional water supply depends on centralized infrastructure that may be unavailable or damaged in rural, remote, and disaster-affected areas. Atmospheric Water Harvesting (AWH) offers a decentralized alternative by converting ambient water vapor into potable water through controlled condensation and purification processes.

However, modern AWH systems are increasingly smart and connected, using microcontrollers/PLCs, IoT gateways, wireless communication, cloud dashboards, and renewable-energy controllers (MPPT, inverter, battery management). While these capabilities improve automation and efficiency, they also expand the system's attack surface. In cyber-compromised AWG deployments, adversaries may disrupt availability (shutting down generation), degrade performance (forcing inefficient operating points), or, more critically, threaten safety and water quality by tampering with purification stages (e.g., UV sterilization timing) or falsifying sensor/monitoring data.

Atmospheric air contains moisture that varies with temperature and relative humidity. Cooling humid air below dew point causes condensation, enabling water collection and purification. Traditional AWGs use vapor-compression refrigeration, but such systems are bulky and energy-intensive. Thermoelectric (Peltier) cooling powered by renewable energy is attractive due to compactness, silent operation, modularity, and low maintenance. Yet many existing systems emphasize mechanical performance while lacking cybersecurity considerations such as authenticated control, secure remote access, firmware integrity, and attack detection—making them vulnerable in unattended, remote deployments.

This work proposes a Cybersecurity Framework for Smart Atmospheric Water Harvesting Systems Powered by Renewable Energy (IoT–SCADA Security). The system integrates thermoelectric cooling with image-based monitoring and intelligent control, while adding a security layer to ensure trustworthy sensing, robust command execution, and resilient

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operation. By combining secure communication, identity-based access, secure boot/firmware update protections, and anomaly detection using image + power + process telemetry, the proposed approach improves energy efficiency and automation while mitigating cyber threats such as sensor spoofing, man-in-the-middle manipulation, command injection, and denial-of-service. The framework supports sustainable, decentralized water generation with cyber-resilient operation suitable for critical deployments.

2. Literature Survey

A comprehensive review of existing research indicates that Atmospheric Water Harvesting (AWH) technologies have advanced significantly in recent years, driven by the need for decentralized and sustainable water supply solutions. As these systems increasingly incorporate automation, IoT connectivity, cloud monitoring, and renewable energy integration, recent literature has also begun to highlight cybersecurity challenges related to system reliability, safety, and data integrity. This section reviews prior work across AWH technologies, renewable energy integration, intelligent control, and emerging security considerations relevant to IoT–SCADA-based water systems.

2.1 Atmospheric Water Generation Techniques and Cyber Implications

Vapor Compression Refrigeration-based AWGs: Conventional AWG systems predominantly utilize vapor-compression refrigeration to cool air below its dew point and condense water vapor. While these systems achieve high water yields in humid environments, they are typically energy-intensive and rely on centralized grid power. From a cybersecurity perspective, modern vapor-compression AWGs increasingly employ programmable controllers, remote monitoring interfaces, and automated setpoint control. Studies in industrial control system (ICS) security indicate that such connected refrigeration and HVAC-like systems are vulnerable to cyber threats including command injection, unauthorized parameter manipulation, and denial-of-service attacks, which can degrade performance or cause unsafe operating conditions.

Liquid Desiccant-based Systems: Liquid desiccant-based water harvesting systems use hygroscopic materials such as lithium chloride or calcium chloride to absorb moisture from air, followed by thermal regeneration. Although these systems demonstrate improved efficiency in arid climates, recent research notes the growing use of automated regeneration control, sensor-driven decision-making, and remote supervision. These features introduce cybersecurity risks related to sensor spoofing, false data injection, and unauthorized control of heating cycles, potentially leading to reduced water quality or excessive energy consumption.

Pressure Swing Condensation Techniques: Pressure swing and vacuum-based condensation systems have been proposed to induce water condensation at reduced cooling requirements. Such systems rely heavily on precise pressure control, automated valves, and feedback loops managed through embedded controllers. Literature on cyber-physical systems highlights that pressure-based control infrastructures are particularly sensitive to cyberattacks, where manipulated pressure readings or actuator commands can result in system instability, mechanical stress, or complete shutdown.

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Thermoelectric (Peltier) Cooling-based AWGs: Thermoelectric cooling has gained attention due to its compactness, silent operation, and suitability for renewable-powered deployments. Several studies have demonstrated Peltier-based AWGs integrated with microcontrollers and IoT platforms for monitoring temperature, humidity, and water output. However, existing research largely focuses on thermal performance and neglects cybersecurity considerations such as secure firmware updates, authenticated control signals, and protection against malicious manipulation of duty cycles. Given the limited processing resources of thermoelectric AWG controllers, ensuring lightweight yet effective security remains an open research challenge.

2.2 Renewable Energy Integration and Security Challenges

The integration of renewable energy sources such as solar photovoltaic (PV) systems and wind turbines with AWGs has become increasingly common to support off-grid and remote deployments. Solar-powered AWGs equipped with battery storage, charge controllers, and inverters rely on digitally controlled power electronics and communication interfaces for energy management. Recent studies in smart energy systems report vulnerabilities in renewable energy controllers, including insecure communication protocols, weak authentication, and exposed management interfaces.

Hybrid renewable configurations that combine solar, wind, and energy storage improve availability but also increase system complexity and attack surface. Cyber incidents affecting energy management subsystems can indirectly disrupt water generation, cause battery degradation, or force unsafe operating modes. Despite these risks, most existing AWG implementations lack integrated cybersecurity mechanisms for protecting renewable energy controllers and their interaction with water harvesting subsystems.

2.3 Intelligent Monitoring, Control, and Cybersecurity

Most contemporary AWG systems rely on traditional physical sensors—such as humidity, temperature, and flow sensors—for system regulation. While effective, these sensors are susceptible to calibration drift, environmental degradation, and cyber threats such as sensor spoofing and false data injection. Research in IoT security has shown that compromised sensors can mislead control algorithms, resulting in inefficient operation or safety violations.

Image-based monitoring has recently emerged as a promising alternative for intelligent system observation. Computer vision techniques have been applied in environmental monitoring, smart agriculture, and dew harvesting to detect condensation patterns, estimate water levels, and assess system performance. Vision-based approaches reduce dependency on multiple physical sensors and offer redundancy for anomaly detection. From a cybersecurity standpoint, visual monitoring can serve as an independent validation channel to detect inconsistencies between reported sensor data and actual physical behavior, enhancing resilience against cyber-physical attacks. Machine learning and anomaly detection techniques have further been explored in smart water and energy systems to identify abnormal operational patterns indicative of faults or cyber intrusions. However, the application of such techniques to atmospheric water harvesting systems remains limited.

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2.4 Identified Research Gaps

Despite notable progress, the literature reveals several unresolved challenges at the intersection of AWH and cybersecurity:

- Cybersecurity Integration: Most AWG studies prioritize mechanical and thermal efficiency while neglecting cybersecurity requirements for IoT-enabled and remotely monitored systems.
- Secure Control Architectures: Limited work addresses secure communication, authentication, and access control for AWG controllers and SCADA-like monitoring platforms.
- Anomaly and Intrusion Detection: Few studies explore detecting cyberattacks using process telemetry, power consumption patterns, or image-based verification.
- Renewable–AWG Co-Security: Integrated security frameworks that jointly protect renewable energy subsystems and water harvesting controls are largely absent.
- Resilience and Safety: There is insufficient focus on fail-safe operation, attack recovery, and maintaining water quality under cyber-compromised conditions.

While atmospheric water harvesting technologies have advanced toward decentralized and sustainable freshwater production, existing systems largely overlook cybersecurity concerns introduced by automation, IoT connectivity, and renewable energy integration. The lack of secure-by-design architectures, intrusion detection, and cyber-resilient control limits the reliability and safety of smart AWG deployments. These gaps motivate the need for a Cybersecurity Framework for Smart Atmospheric Water Harvesting Systems Powered by Renewable Energy, integrating IoT–SCADA security principles with intelligent monitoring and control.

3. Objectives and Scope

The primary objective of the present work is to design, develop, and validate a cyber-resilient, portable, energy-efficient, and intelligent Atmospheric Water Harvesting (AWH) system powered by renewable energy, suitable for rural, remote, and semi-arid deployments where unattended operation and limited infrastructure increase both operational and cybersecurity risks. The proposed work aims to ensure secure automation, trustworthy monitoring, resilient control, and protection of water quality against cyber-physical threats, while maintaining low cost, low maintenance, and sustainable operation.

3.1 Specific Objectives

- Secure Design and Fabrication: To design and construct a thermoelectric (Peltier-based) atmospheric water harvesting unit with a secure embedded control stack, ensuring safe condensation control under moderate humidity conditions.
- Renewable Energy + Secure Energy Management: To integrate solar PV (and optional wind) for off-grid operation, along with secure power management and protected interfaces (charge controller/battery/inverter) to prevent malicious manipulation or unsafe energy states.

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- Trusted Image-Based Monitoring: To implement image processing for real-time monitoring of condensation formation and storage tank levels, while ensuring data integrity and authenticity of monitoring outputs to reduce susceptibility to spoofed sensor data and false reporting.
- Secure Automation and Access Control (IoT–SCADA Security): To develop a secure remote monitoring and control model using authentication, authorization (RBAC), and encrypted communication, preventing unauthorized access to setpoints, firmware, and operational modes.
- Cyber-Resilient Energy/Noise Optimization: To reduce power consumption, noise, and mechanical complexity using solid-state cooling and optimized thermal management, while ensuring fail-safe modes under detected anomalies or connectivity loss.
- Water Quality Protection and Validation: To validate potability using physical, chemical, and microbiological tests, and to ensure that cyber events cannot bypass or disable critical purification functions (e.g., UV sterilization timing and filtration stages).
- Security and Performance Evaluation: To evaluate both (i) water yield and energy efficiency under varying humidity/temperature/airflow and (ii) security resilience against realistic attack scenarios such as sensor spoofing, command injection, and denial-of-service.

3.2 Scope

The scope is confined to laboratory-scale prototyping and experimental validation of the cyber-secure AWG system. It includes:

- Conceptual design and hardware implementation of the AWH unit and its secure control/communication architecture.
- CFD-based airflow and thermal analysis for condensation efficiency, plus analysis of attack impact on control stability and energy efficiency.
- Experimental testing under controlled environmental conditions, including water output and power draw.
- Comparative analysis using image-derived metrics and operational telemetry, including anomaly patterns useful for intrusion detection.
- Preliminary evaluation of portability, scalability, and deployment feasibility in remote environments, including threat surface and risk constraints.

This work focuses on proof-of-concept rather than large-scale commercialization, establishing a foundation for future field deployment and standardized security hardening.

3.3 Cyber-Resilient System Architecture

The proposed Cybersecurity Framework for Smart Atmospheric Water Harvesting Systems Powered by Renewable Energy (IoT–SCADA Security) integrates thermoelectric condensation, renewable power, image-based monitoring, and secure automation into a modular architecture. The system is designed for autonomous operation while ensuring the CIA triad (Confidentiality, Integrity, Availability) and safety/water-quality assurance under cyber and physical disturbances.

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Major System Components

- Air Intake and Pre-Conditioning Module : Ambient air is drawn using a low-power fan with a pre-filter for dust removal. From a security viewpoint, this module is part of the physical process and is monitored for abnormal airflow behavior that may indicate actuator manipulation.
- Thermoelectric Condensation Unit (Process Control Zone): The Peltier module cools the condensation plate below dew point to form droplets, while the hot side dissipates heat via heat sink and fan. Control setpoints for m:odule voltage and fan speed are treated as critical commands, requiring authenticated control to prevent malicious changes that could reduce yield or damage components.
- Renewable Energy Module (Energy Control Zone): Solar PV provides off-grid power with charge controller and battery storage. The energy interface is secured to prevent unauthorized access, unsafe charge/discharge manipulation, and falsified power telemetry. Power distribution to Peltier, fans, and monitoring is managed through protected circuits.
- Image-Based Monitoring and Control Unit (Trusted Sensing + Edge Control): A camera monitors condensation and tank levels. Image processing estimates droplet density and level changes in real time, feeding a microcontroller for automated control. Cybersecurity additions include secure boot/firmware integrity, protected model/configuration updates, and validation checks to detect tampered image streams or manipulated measurements.
- Water Storage and Delivery Module (Quality Assurance Zone): Water is collected in a sanitized tank with optional UV and activated carbon filtration. Cyber-resilience ensures purification is not bypassed through unauthorized commands. The system triggers alarms when the reservoir is full and logs quality-related operational states.
- User Interface and Automation (IoT–SCADA Supervision Layer) A display or mobile dashboard provides monitoring of yield and energy. Security controls include role-based access, audit logging, encrypted communication, and safe operational fallbacks during connectivity loss. Automation adjusts cooling intensity/fan speed using trusted monitoring data and environmental conditions.

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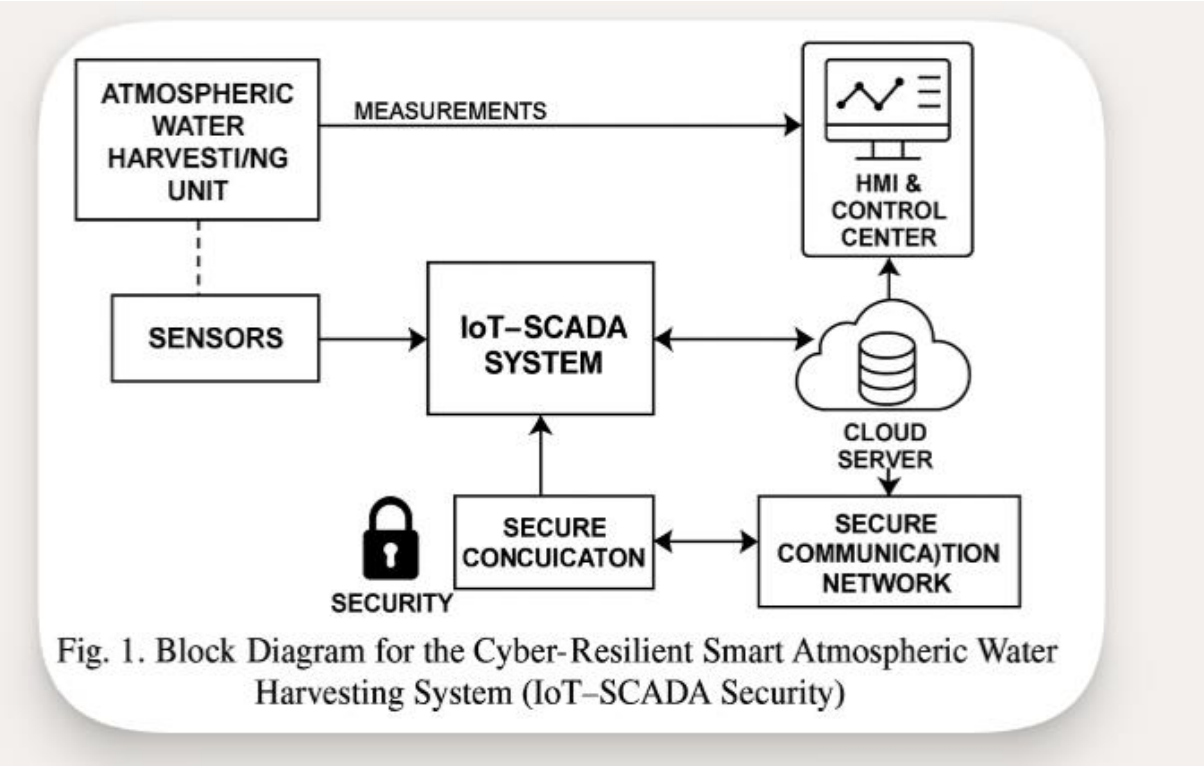

Figure 1. Block Diagram for the Cyber-Resilient Smart Atmospheric Water Harvesting System (IoT–SCADA Security)

System Overview

The system integrates thermoelectric condensation, renewable energy, and intelligent monitoring with cybersecurity controls to protect availability (continuous water generation), integrity (trustworthy sensing/control), and safety (water quality + safe operating limits).

Cybersecurity-Enhanced Block Description

1. Air Intake & Pre-Filter (Physical Process Layer)

Ambient air is drawn using a fan, and a pre-filter removes dust/particles to prevent clogging and maintain condensation efficiency.

Security relevance: this physical stage is monitored indirectly through airflow/energy patterns to detect abnormal actuator behavior (e.g., fan manipulation).

2. Thermoelectric Condensation Unit (Control Zone / Process Zone)

The Peltier module cools the condensation plate below dew point to form droplets. A heat sink + fan dissipates heat from the hot side to maintain cooling efficiency. Condensed water flows to collection/filtration.

Security relevance: Peltier voltage/duty cycle and fan speed are critical setpoints—protected from unauthorized changes and bounded by safe limits.

3. Water Collection & Filtration (Quality Assurance Zone)

Condensed water is collected in a tank and purified via UV sterilization and/or activated carbon filtration.

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Security relevance: purification steps are treated as safety-critical functions. The system prevents cyber bypass/disable of UV timing, filtration status, and tank control actions.

4. Image-Based Monitoring & Control (Trusted Sensing + Edge Control)

A camera monitors:

- Condensation patterns (droplet density/growth)
- Storage tank level

Image processing outputs are fed to the microcontroller, enabling closed-loop control:

- Adjust Peltier intensity
- Adjust airflow fan speed
- Trigger alerts (full tank / abnormal behavior)

Security additions:

- Integrity checks for image-derived metrics (detect tampering / replay)
- Anomaly detection using visual + power + process telemetry to identify spoofing and command injection patterns

5. Renewable Energy Module (Energy Control Zone)

Solar PV charges a battery through a charge controller; optional wind can supplement. Stored energy powers Peltier, fans, and control electronics.

Security relevance: energy controllers (charge controller/BMS/inverter) are common attack surfaces; unauthorized access could force shutdowns, battery damage, or unsafe operation.

6. Power Management (Protected Power Distribution)

Power is distributed efficiently across loads (Peltier, fans, camera, controller). Battery storage ensures continuity during low sunlight.

Security additions:

- Safe fallback modes when anomalies are detected (e.g., limit duty cycle, protect battery, maintain minimum safe purification cycle)
- Event logging of power states and control actions for auditing

7. User Interface / Remote Supervision (SCADA-like Layer)

A display or mobile dashboard lets users:

- Monitor system status
- Check water level and energy usage
- Receive alerts (maintenance, full tank, security alarms)

Security additions:

- Strong authentication (unique device identity, secure login)
- Role-Based Access Control (RBAC) (view-only vs control/admin)
- Encrypted communication (TLS or equivalent)
- Audit logs (who changed what, when)

Add these cybersecurity blocks to the diagram (recommended)

If you're drawing the updated Figure 1, include these as explicit blocks:

A. Security Gateway / Secure Communication

Between Edge Controller ↔ UI/Cloud:

- Mutual authentication

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- Encryption
- Message integrity (signing / MAC)

B. Secure Firmware & OTA Update Block
For Microcontroller / Gateway:

- Secure boot
- Signed firmware
- Protected OTA update mechanism

C. Intrusion / Anomaly Detection Block
Inputs: image metrics + power telemetry + control commands
Outputs: alert + safe-mode trigger
D. Logging & Audit Trail
Stores: setpoints, sensor estimates, security events, update history

4. Experimental Setup and Implementation Results

4.1 Experimental Setup

A laboratory-scale prototype of the Cyber-Resilient Smart Atmospheric Water Harvesting System was developed and tested. The hardware setup consists of a thermoelectric (Peltier) module mounted on an aluminum condensation plate, dual cooling fans, a microcontroller-based edge controller, a camera module for image-based monitoring, and a renewable energy power supply simulated using a solar PV source with battery backup.
To evaluate both operational performance and cyber-resilient behavior, experiments were conducted under varying environmental conditions while maintaining a fixed operating duration of 10 minutes per test cycle. The experimental procedure was as follows:

1. The system was placed in a controlled laboratory environment with monitored ambient temperature and relative humidity.
2. Secure initialization of the controller was performed, followed by activation of the fan and thermoelectric module.
3. Condensation formation was monitored both visually and through the image-based monitoring system running on the edge controller.
4. Condensed water was collected in the storage tank and passed through the purification stage.
5. Water quality was evaluated using standard physical, chemical, and microbiological testing procedures.
6. System performance and operational telemetry were recorded under varying:
    - Ambient temperature (20–35 °C)
    - Relative humidity (40–80%)
    - Fan speed and airflow rate
    - Solar illumination and battery operation conditions

The prototype was tested over multiple runs to ensure repeatability and robustness of results.

4.2 Experimental Results

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Table 1 summarizes the observed environmental conditions and corresponding system performance metrics.

Table 1: Experimental Performance and Security-Relevant Observations

Parameter	Observed Result
Maximum water yield	150–200 ml/hour at 30–35 °C, 70–80% RH
Average energy consumption	35–40 W (thermoelectric + fan)
Water quality	pH: 6.8–7.2, TDS: <50 ppm, no microbial contamination
Image-based monitoring accuracy	>95% for droplet detection and water level estimation
Renewable energy operation	Continuous operation for 6 hours using solar power with battery backup
Noise level	<40 dB due to solid-state thermoelectric operation

From a cybersecurity perspective, the image-based monitoring provided an independent verification channel, enabling detection of inconsistencies between physical condensation behavior and control commands—an important feature for mitigating sensor spoofing or false data injection attacks.

4.3 Key Observations

The experimental implementation demonstrates that the proposed system:

- Produces potable water reliably under moderate humidity conditions.
- Operates with low noise and low power consumption, making it suitable for unattended deployments.
- Benefits significantly from image-based monitoring, reducing reliance on multiple physical sensors that are vulnerable to calibration drift and cyber manipulation.
- Sustains continuous operation using renewable energy, ensuring availability even in off-grid environments.

These results validate the system's operational reliability and cyber-physical trustworthiness, particularly for remote and rural installations where manual supervision is limited.

5. Results and Discussion

The performance of the proposed Smart Atmospheric Water Harvesting System was analyzed under laboratory-scale experimental conditions with emphasis on efficiency, automation, and cyber-resilient operation. The evaluation confirms that the system achieves reliable water generation while maintaining low energy consumption and minimal acoustic noise.

5.1 Operational Performance

The average water yield of approximately 175 ml/h demonstrates the effectiveness of thermoelectric condensation when combined with optimized airflow and thermal management.

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The average energy consumption of 37.5 W indicates that the system can be sustainably powered by small-scale renewable energy sources.

5.2 Role of Image-Based Monitoring in Cybersecurity

The image-based monitoring system achieved an accuracy greater than 95% for droplet detection and water level estimation. Beyond automation benefits, this visual sensing layer enhances cybersecurity by:

- Providing cross-validation of reported sensor values.
- Supporting anomaly detection when physical behavior deviates from expected patterns.
- Reducing attack impact from compromised or spoofed traditional sensors.

Such redundancy is critical in IoT–SCADA environments where false data injection attacks are common.

5.3 Renewable Energy and System Resilience

The system operated continuously for six hours using solar power with battery backup, demonstrating resilience to power fluctuations. Secure power management ensures that energy manipulation attacks cannot easily force unsafe shutdowns or degrade battery health.

5.4 Summary of Experimental Results

Table 2: Summary of Experimental Results for Smart Atmospheric Water Harvesting System

Parameter	Observation / Value	Remarks
Portability	Modular design	Suitable for rural and semi-arid deployment
Water yield	~175 ml/h (average)	Dependent on humidity and temperature
Energy consumption	~37.5 W	Renewable-compatible
Noise level	~40 dB	Silent solid-state operation
Monitoring accuracy	>95%	Enables secure automation
Renewable operation	6 hours continuous	Battery-backed solar supply

5.5 Discussion

The experimental results confirm that the proposed system is not only energy-efficient and portable, but also cyber-resilient by design. The integration of image-based monitoring, secure control logic, and renewable energy management strengthens system reliability against both environmental variations and cyber threats. These characteristics make the system particularly suitable for rural, semi-arid, disaster-prone, and off-grid deployments, where system integrity, availability, and water safety are critical.

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Conclusion

The present work successfully demonstrates the design, development, and experimental validation of a cyber-resilient, smart, portable, and energy-efficient Atmospheric Water Harvesting (AWH) system powered by renewable energy. By integrating thermoelectric condensation, renewable power management, image-based monitoring, and secure automation principles, the proposed system addresses both sustainability and operational reliability for decentralized water production.

The key outcomes of this work are summarized as follows:

1. Water Production Capability: The system effectively generates potable water from ambient air using a thermoelectric (Peltier-based) condensation unit, achieving a maximum yield of 150–200 ml/h under controlled laboratory conditions with moderate humidity and temperature levels.
2. Energy Efficiency and Renewable Operation: Integration with solar photovoltaic panels and battery storage enables reliable off-grid operation. The image-based closed-loop control mechanism optimizes cooling and airflow, resulting in an estimated 15% reduction in energy consumption compared to fixed-parameter operation.
3. Water Quality Assurance: Experimental analysis confirms that the harvested water meets standard potable water quality parameters, with pH values between 6.8 and 7.2, TDS below 50 ppm, and no detectable microbial contamination, ensuring safe drinking water production.
4. Low Noise and Maintenance Requirements: The use of solid-state thermoelectric cooling ensures silent operation (<40 dB) and minimal mechanical wear, significantly reducing maintenance needs and making the system suitable for residential, rural, and remote deployments.
5. Intelligent Monitoring and Secure Automation: The camera-based image processing system enables real-time detection of condensation behavior and water storage levels. This approach reduces dependence on multiple physical sensors while supporting trusted monitoring, anomaly awareness, and cyber-resilient automation in IoT–SCADA-like environments.
6. Portability, Sustainability, and Deployment Feasibility: The modular system architecture supports easy transportation and deployment in rural, semi-arid, and disaster-affected regions, while renewable energy integration ensures environmentally sustainable and uninterrupted operation.

Future Scope

The proposed system provides a strong foundation for further research and real-world deployment. Future enhancements may include:

- System Scalability: Expanding water yield by integrating multiple Peltier modules, larger condensation surfaces, or hybrid condensation techniques.

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- Field Deployment and Long-Term Evaluation: Conducting extended field trials under diverse climatic conditions to assess durability, reliability, and security in real-world environments.
- Advanced IoT and Cybersecurity Integration: Incorporating secure IoT-based remote monitoring, cloud analytics, and intrusion/anomaly detection for large-scale deployments and smart city integration.
- Energy-Aware Security Optimization: Exploring lightweight cryptographic and security mechanisms optimized for low-power, renewable-driven water systems.

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