

# Design and Development of an Atmospheric Water Harvesting System Using Solar-Powered Thermoelectric Cooling for Hot and Humid Water-Scarce Areas

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DOI: <https://doi.org/10.47772/IJRISS.2026.100800844>

Received: 10 August 2026; Accepted: 15 August 2026; Published: 18 September 2026

## ABSTRACT

Atmospheric Water Harvesting (AWH) using Solar-Powered Thermoelectric Cooling (TEC) offers a decentralised, renewable means of extracting water vapour from humid air in hot, water-scarce regions. A major challenge in AWH is achieving efficient, low-maintenance cooling to condense moisture, a need that TEC modules address through their solid-state reliability. This study designs, develops and evaluates an AWH prototype that integrates a TEC module, a copper coil condenser, DC cooling fans, a water circulation pump and a solar-battery power supply to analyze temperature behavior, water collection and energy efficiency. Ambient water is circulated through the TEC to cool a copper coil below the dew point, inducing continuous condensation. The prototype was tested inside a sealed chamber over one-hour operating periods to compare copper coil orientation, coolant flow rate, and daytime versus night-time operation. Results show the horizontal copper orientation achieved a more uniform, lower steady-state surface temperature (20.5-21.0°C) than the vertical orientation (21.5-22.5°C), producing 55.4 mL of water compared to 33.0 mL, an increase of about 68%. Raising the coolant flow rate from 600 L/h to 1000 L/h increased water yield from 55 mL to 94 mL, while 800 L/h gave the lowest average copper surface temperature (21.1°C). Night-time operation consistently outperformed daytime operation, collecting an average of 83 mL compared to 76 mL, owing to lower ambient temperature and higher relative humidity. The system achieved a peak yield of 94 mL/h, comparing favorably with similar TEC-based AWH prototypes reported in the literature. Overall, the developed system demonstrates reliable, energy-efficient performance under hot and humid tropical conditions, supporting its potential as a practical, off-grid solution for atmospheric water harvesting in water-scarce areas.

**Keywords:** Atmospheric Water Harvesting, Thermoelectric Cooling, Solar Energy, Condensation, Copper Coil Condenser

## INTRODUCTION

Access to clean water is becoming increasingly critical as global population and water demand continue to rise. Over 70% of the world's freshwater is used for agriculture, and although global water resources have remained largely constant, clean water demand has doubled over the past 20 years. Many water-stressed regions, especially tropical countries near the equator such as Malaysia, are nonetheless rich in atmospheric moisture: Malaysia experiences an average relative humidity of 84-88% and temperatures of 23-32°C, conditions that are ideal for harvesting atmospheric water. Similarly, Indonesia has abundant annual water resources yet still struggles with clean water access in rural areas, where only 39% of urban residents and 5% of rural residents have piped water access despite a warm, humid tropical climate. These conditions make Atmospheric Water Harvesting (AWH) a promising, decentralized alternative to conventional water infrastructure.

One of the most promising AWH techniques is Thermoelectric Cooling (TEC), based on the Peltier effect, in which an electric current creates a temperature difference across a semiconductor module so that one side cools while the other heats. The cold side can be used to cool a surface below the dew point of the surrounding air, inducing condensation. TEC systems are compact, silent and contain no moving parts, making them attractive

for decentralized, solar-powered water generation. Riahi et al. [5] demonstrated a medium-scale AWH system with 18 TEC modules in Malaysia, producing 3.43 L of water in 24 hours and 7 L in 48 hours, with peak yield occurring at night when humidity was high and temperature was low. Djafar et al. [2] tested a 12-module TEC-based AWH system across laboratory, residential and coastal environments in Indonesia, achieving up to 7.75 mL/h in coastal conditions. Sanaye et al. [6] developed a closed-loop, water-cooled TEC-based AWH system achieving 0.56 mL/h·W energy efficiency and a water production cost of \$0.24/L, while Tashtoush and Alshoubaki [7] reported an off-grid solar-powered AWH system capable of harvesting up to 100 L/day in coastal climates. Wang et al. [8] showed that lowering the condensing surface temperature of a TEC unit from 5°C to –10°C increased water productivity by up to 186%, and Kadhim et al. [3] and Anowar et al. [1] further confirmed the feasibility of solar-powered, TEC-based atmospheric water generators in humid climates.

Despite this progress, many existing AWH technologies still require high energy input or rely on refrigerants that are harmful to the environment, limiting their adoption, particularly in off-grid and rural areas. In line with United Nations Sustainable Development Goal 6 (Clean Water and Sanitation) and Sustainable Development Goal 13 (Climate Action), there is a need for compact, low-energy AWH systems that use renewable power sources. This motivates the development of a TEC-based AWH system powered by solar energy, aimed at reducing reliance on conventional water supply methods while minimizing the carbon emissions associated with water production.

The objectives of this study are to (1) design an AWH system utilizing a Thermoelectric Cooling module, (2) develop a prototype AWH system that integrates a TEC module with design modifications aimed at maximizing water condensation and minimizing energy consumption, and (3) analyze the operational performance of the developed AWH system under varying real-world atmospheric conditions, in terms of water production rate, energy efficiency and overall performance. The scope of the study covers the design and fabrication of a 600 mm × 400 mm × 400 mm AWH prototype using a TEC module, and its testing under different copper coil orientations, coolant flow rates, and daytime/night-time conditions to evaluate its potential in supporting SDG 6 and SDG 13.

## METHODOLOGY

### System Design and Working Principle

The system extracts moisture from humid air and converts it into liquid water through condensation. When air is cooled below its dew point, water vapor condenses into droplets that can be collected. To achieve this, the system uses a TEC module operating on the Peltier effect: when a direct current passes through the module, one side becomes cold while the other becomes hot. The cold side is placed in thermal contact with a copper coil condenser, cooling it below the dew point of the surrounding humid air and inducing continuous condensation, while the hot side is cooled using a circulating water loop to sustain the temperature gradient. The operation of the TEC module can be described using its Seebeck coefficient, electrical resistance and thermal conductance, which together determine the heat absorbed at the cold side ( $Q_c$ ), the heat rejected at the hot side ( $Q_h$ ), and the electrical power consumed ( $P$ ) as functions of the applied current and the temperature difference across the module,  $\Delta T = T_h - T_c$ .

### System Components

The core cooling component is a Liquid Series LA-075-24-02 TEC module, which provides a maximum cooling capacity of 71 W at zero temperature difference, a maximum  $\Delta T$  of 42°C, and a coefficient of performance of up to 1.2, operating at a nominal 24 VDC. The condenser is a 10 mm outer-diameter phosphorus-deoxidized copper coil (C1220T), chosen for its high thermal conductivity (~4 W/m·°C) and its ability to support dropwise condensation for efficient water runoff. Airflow is provided by SUNVN YD6010HSL DC brushless axial fans (24 V, 0.06 A, 4000 RPM) positioned at the inlet and outlet of the test chamber. A regulated 24 VDC, 10 A power supply drives the TEC module and fans, while an AC submersible pump (220 V, 12 W, up to 600 L/h) circulates ambient water from an EPS cooler-box water tank through the hot side of the TEC to remove heat. Condensed water drains into a collection tray positioned beneath the copper coil. The system is powered by a 100 W monocrystalline solar panel, a solar charge controller, two 12 V 7.2 Ah AGM batteries connected in

parallel (14.4 Ah total), and a 4000 W pure sine wave inverter, enabling off-grid operation. Temperature data at the chamber, copper coil, ambient and water-tank locations were recorded using K-type thermocouples connected to an ADAM-4019+ data acquisition module, while a DHT22 sensor logged ambient temperature and relative humidity.

## Experimental Setup and Testing Procedure

The prototype was assembled inside a sealed test chamber to minimize external airflow interference, with the TEC module mounted on a flat surface and the copper coil fixed to its cold side using thermal paste. The system was evaluated through one-hour continuous test runs under moderate relative humidity (68-91%). Three experimental conditions were investigated: (1) copper coil orientation, comparing a vertical and a horizontal coil configuration under identical TEC input, airflow and coolant flow rate (600 L/h); (2) coolant flow rate, comparing 600 L/h, 800 L/h and 1000 L/h using the better-performing coil orientation; and (3) daytime versus night-time operation, with water collection recorded over five consecutive testing days for each condition. Chamber, copper coil, ambient and coolant temperatures were logged continuously, and condensed water volume was measured using a graduated container.

## RESULTS AND DISCUSSION

### Temperature Performance

Over the one-hour test period, the chamber temperature dropped from approximately 29.2°C to 27.6°C shortly after activation, then stabilised between 27.5°C and 28.0°C, before rising slightly to about 28.4°C towards the end of the run, indicating effective but gradually saturating cooling within the enclosed chamber. The water-tank coolant temperature briefly rose from about 24.0°C to a peak of 25.8°C as it absorbed heat from the TEC hot side, before decreasing steadily and stabilising at approximately 19.2°C after around 30 minutes, confirming effective heat removal by the water circulation loop.

### Effect of Copper Coil Orientation

The vertical and horizontal copper coil orientations were compared at a fixed coolant flow rate of 600 L/h. The horizontal orientation cooled more rapidly and settled at a lower, more stable steady-state temperature of 20.5-21.0°C, compared with 21.5-22.5°C for the vertical orientation. This translated directly into water yield: as shown in Figure 1, the horizontal orientation produced 55.4 mL of condensed water within one hour, compared with 33.0 mL for the vertical orientation, an increase of approximately 68%. The improvement is attributed to more uniform surface cooling and improved condensate retention on the horizontal coil, which promotes droplet coalescence and drainage, whereas the vertical orientation is more prone to uneven condensate formation and weaker gravitational drainage along the coil surface.

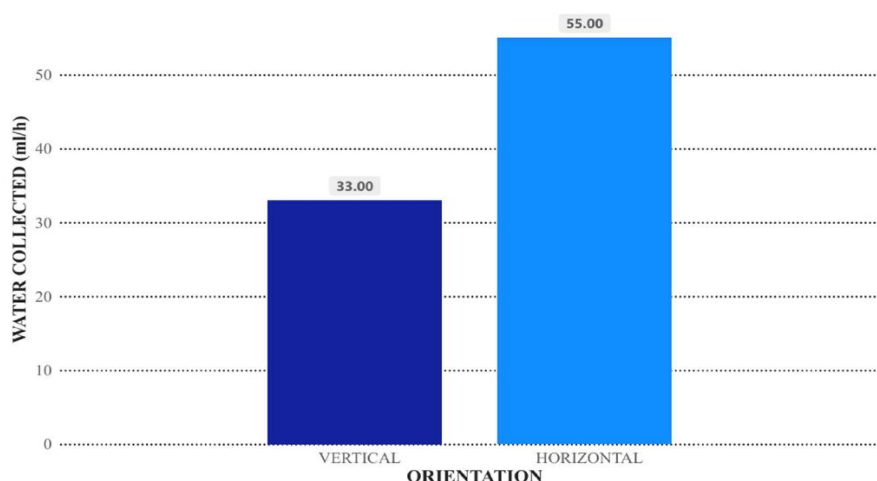


Figure 1: Total water collected for vertical and horizontal copper coil orientations

## Effect of Coolant Flow Rate

Using the horizontal coil orientation, three coolant flow rates were tested: 600 L/h, 800 L/h and 1000 L/h (Figure 2). At 600 L/h, the copper surface stabilized at 20.5-21.0°C and the system collected 55 mL of water. At 800 L/h, the surface temperature stabilized slightly higher, at 22.0-22.5°C, but the improved coolant circulation increased water collection to 85.8 mL. At 1000 L/h, the surface temperature stabilized at 20.7-21.2°C and water collection reached the highest value recorded, 94 mL. When comparing average steady-state coil temperature alone, 800 L/h produced the lowest value (21.1°C), against 21.7°C at both 600 L/h and 1000 L/h, indicating that beyond a certain point additional coolant flow reduces contact time between the coolant and the heat exchanger without further lowering average temperature. Nevertheless, 1000 L/h produced the highest overall water yield, showing that increased coolant circulation and thermal stability, rather than the lowest instantaneous surface temperature alone, is the key driver of water production in this system.

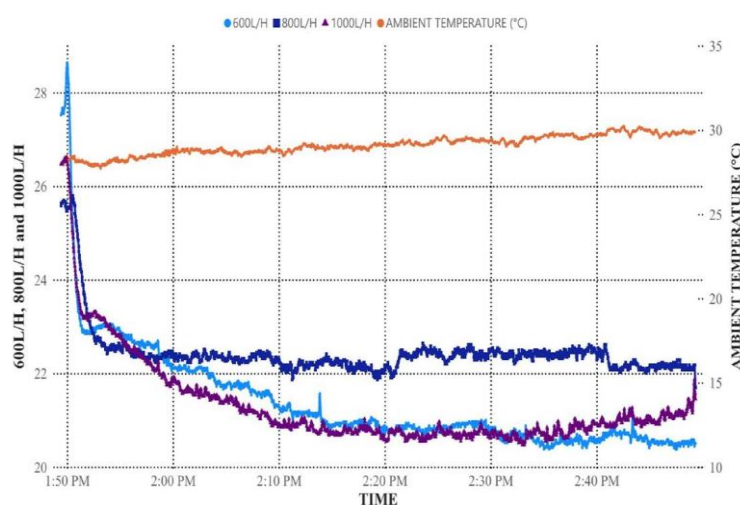


Figure 2: Effect of coolant flow rate on copper coil surface temperature

## Daytime versus Night-time Performance

Water collection was recorded over five consecutive days for daytime and night-time operation (Figure 3). Night-time operation produced a higher average yield of 83 mL, compared with 76 mL for daytime operation. This improvement is attributed to the lower ambient temperature and higher relative humidity typically present at night, which increase the temperature difference between the ambient air and the cooled condenser surface and enhance the condensation rate. Daytime operation showed greater variation between testing days, reflecting its greater sensitivity to fluctuating temperature and humidity conditions, whereas night-time yields remained more consistent.

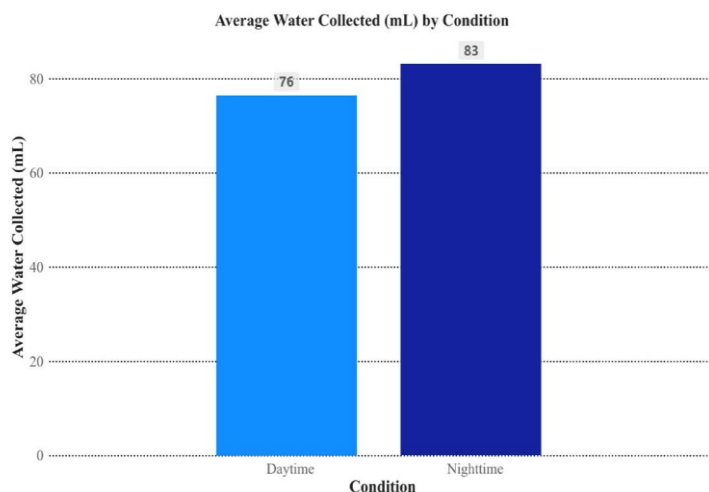


Figure 3: Comparison of average water collected during daytime and night-time operation

## Benchmarking with Existing Systems

Table 1 compares the maximum water yield, relative humidity and power consumption of the developed system against comparable TEC-based AWH prototypes reported in the literature. The developed system achieved a peak yield of 94 mL/h at 82.5% relative humidity and 117.7 W power consumption, the second-highest water collection performance among the compared systems while consuming less power than several higher-output designs, indicating a favorable balance between water production and energy efficiency.

| Prototype     | Water Condensed (mL/h) | Relative Humidity (%) | Power Consumption (W) | Reference |
|---------------|------------------------|-----------------------|-----------------------|-----------|
| Present Study | 94                     | 82.5                  | 117.7                 | This work |
| Cano Perez    | 39                     | 70                    | 70                    | —         |
| Kadhim et al. | 20                     | 75                    | 70                    | [3]       |
| Riahi et al.  | 145                    | 55–85                 | 1000                  | [5]       |
| Djafar et al. | 7.75                   | 72.27–83.01           | 270                   | [2]       |

Table 1: Maximum water collected by comparable AWH systems using thermoelectric cooling modules

## CONCLUSION

This study designed, developed and experimentally evaluated a solar-powered, thermoelectric-cooling-based Atmospheric Water Harvesting system for hot and humid, water-scarce areas. The prototype integrated a TEC module, a copper coil condenser, a water-cooled heat rejection loop, and a solar-battery power supply, and was validated through systematic testing of copper coil orientation, coolant flow rate, and daytime versus night-time operation. The results showed that thermoelectric cooling provided stable and reliable temperature control, that the horizontal copper coil orientation achieved higher condensation efficiency than the vertical orientation, that increasing coolant flow rate improved water yield up to 1000 L/h, and that night-time operation consistently outperformed daytime operation due to more favorable ambient conditions. The system achieved a peak water yield of 94 mL/h, comparing favorably with similar published TEC-based AWH prototypes. By integrating renewable solar energy for off-grid operation, this work supports Sustainable Development Goal 6 (Clean Water and Sanitation) and Sustainable Development Goal 13 (Climate Action). Future work may explore multiple or larger-area TEC modules, finned or coated condenser surfaces, MPPT-based solar-battery energy management, and IoT-based real-time monitoring to further improve water yield, energy efficiency and scalability toward practical deployment.

## ACKNOWLEDGEMENTS

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for the facilities and support provided throughout this project, and all laboratory staff and colleagues who assisted with the fabrication and testing of the prototype.

## REFERENCES

1. A. Anowar, S. U. Nayeem, and S. S. Wriddhi, “Alternative source of water using atmospheric water generator by using thermoelectric cooling method and its potential use for sustainable development,” 2024.
2. Z. Djafar et al., “Atmospheric Water Harvesting Using Thermoelectric Cooling Technology,” *Int. J. Des. Nat. Ecodynamics*, vol. 18, no. 4, pp. 1011–1016, 2023. <https://doi.org/10.18280/ij dne.180430>

3. T. J. Kadhim, A. K. Abbas, and H. J. Kadhim, "Experimental study of atmospheric water collection powered by solar energy using the Peltier effect," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 671, no. 1, 2020. <https://doi.org/10.1088/1757-899X/671/1/012155>
4. G. Raveesh, R. Goyal, and S. K. Tyagi, "Advances in atmospheric water generation technologies," *Energy Convers. Manag.*, vol. 239, p. 114226, 2021. <https://doi.org/10.1016/j.enconman.2021.114226>
5. A. Riahi et al., "Performance investigation of 18 thermoelectric cooler (TEC) units to supply continuous daily fresh water from Malaysia's atmosphere," *Sustainability*, vol. 13, no. 3, pp. 1–16, 2021. <https://doi.org/10.3390/su13031399>
6. S. Sanaye, A. Shourabi, and D. Borzuei, "Sustainable water production with an innovative thermoelectric-based atmospheric water harvesting system," *Energy Reports*, vol. 10, pp. 1339–1355, 2023. <https://doi.org/10.1016/j.egyr.2023.07.062>
7. B. Tashtoush and A. Y. Alshoubaki, "Solar-off-grid atmospheric water harvesting system: Performance analysis and evaluation in diverse climate conditions," *Sci. Total Environ.*, vol. 906, p. 167804, 2024. <https://doi.org/10.1016/j.scitotenv.2023.167804>
8. J. Wang, Y. Suo, H. Lou, Y. Ye, and Z. Zhang, "Optimization of a thermoelectric cooler-based system for atmospheric water production in terms of temperature of condensing surface," *Case Stud. Therm. Eng.*, vol. 54, p. 104000, 2024. <https://doi.org/10.1016/j.csite.2024.104000>
9. J. Wang, Z. Yang, Z. Li, H. Fu, and J. Chen, "Comprehensive review on atmospheric water harvesting technologies," *J. Water Process Eng.*, vol. 69, p. 106836, 2025. <https://doi.org/10.1016/j.jwpe.2024.106836>