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Article

Design and Performance Evaluation of a Portable Solar-Powered Atmospheric Water Harvesting System Using Enhanced Condensation Techniques

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Abstract: A major global problem is the scarcity of fresh water, especially in arid regions where traditional sources are being depleted and polluted at an increasing rate.. Renewable energy (AWH) technology has emerged as a promising solution to this crisis in a sustainable manner. This study examines the performance of a portable solar and battery-powered water recovery system with a compression cooling cycle. The system consists of a DC compressor, condensing network, intake fan and humidification chamber. A comprehensive pilot study was performed to evaluate the impact of variation in air intake velocities (tested at 0.65, 0.75 and 0.83 m/s) and to determine the impact of condensation enhancers, namely, a wire-mesh and an ultrasonic fog generator. Experimental results show that the base yield of the reference system without any improvements was 44 ml, while the application of the metal mesh and the fog generator alone increased the output to 60 ml and 101 ml, respectively. The combination of fog generator and metal grille gave a maximum yield of 140 ml for 5 hours operating time and the optimal value of air intake speed is 0.65 m/s (the best value for the tested speeds) which is a significant improvement of 218% compared to the base condition . Parametric assessment also indicated a better performance at night (139 ml) than during the day (120 ml) at this speed optimum. These results imply that the combined synergistic effect of fog generation with grid surfaces enhances the condensation efficiency significantly, thus offering compact and highly efficient designs for sustainable and climate-friendly freshwater production in Iraq, especially in Karbala
Keywords: Atmospheric water harvesting, Water scarcity, Metal–organic frameworks, Sustainable water supply

1. Introduction

Along with Climate Change, Water scarcity is emerging to be a big challenge. As population and industrialisation continue to grow, pressure on fresh water is ever increasing, with two thirds of the world's population living in water-scarce areas.

(Meng, Dang and Suib, 2022) .

Water is a rare vital resource that joins the environment and climate, and it is known that 70% of the earth's surface is submerged with sea water, with only 1% representing ice at the poles, and humans can reach only 1% of the world's water. In the 20 th century, populationlk tripled and water consumption increased tenfold. As demand rises, freshwater scarcity is becoming a concern for sustainable human development. The effects of prolonged drought are already visible and severe in 2050, as shown in figure (1), population growth of 8.9 billion could lead to severe water shortages for 3.5 billion people. Currently, over a billion people lack access to a continuous supply of drinking water, and 3 to 4 billion lack sufficient and stable water.

Since the 1980s water consumption has increased by 1% annually and is projected to increase by 20 to 30% by 2050 due to population growth, rapid socio-social development, and increasing industrial and domestic demand. The current trends indicate that by 2030, 1/3 of the global population will be short of water and by 2025, 2/3 will be “water stressed” **(Khtiri prof Marco Simonetti Vincenzo Gentile, 2020)**

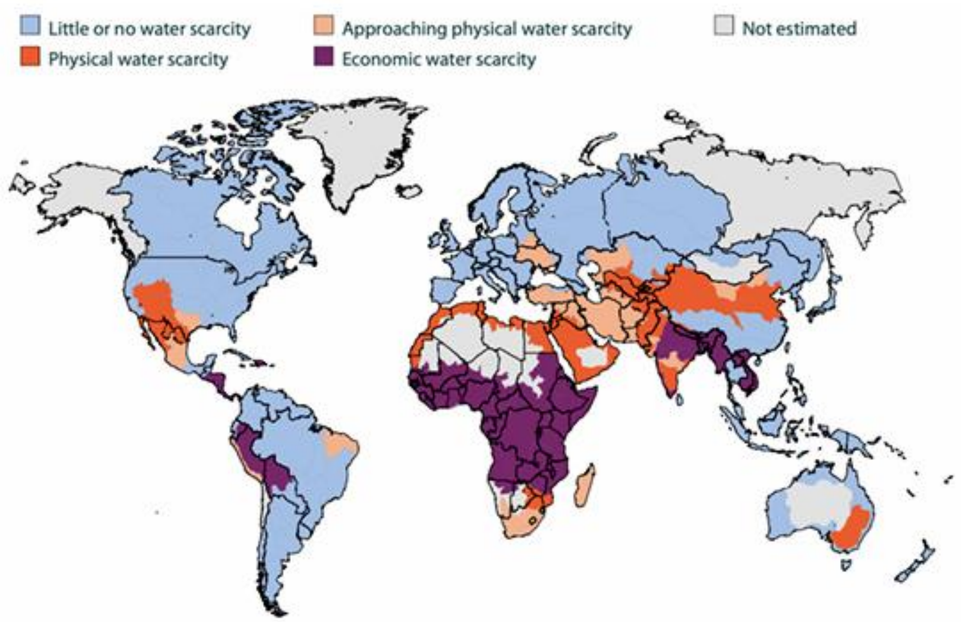

Figure 1 water scarcity across the globe- (Khtiri prof Marco Simonetti Vincenzo Gentile, 2020)

Water is essential for human life and various industrial processes; however, rising global demand and diminishing water resources have created a critical situation, as noted in the UNESCO report on water development (2015).

(Thesis, no date) (Yang *et al.*, 2021)

Climate change is the main driver of the greatest challenges for modern civilization. The impacts of climate change are increasingly evident, with drought being a major symptom that is worsening in some parts of the world. identify desertification as one of the main drivers of climate change. Desertification is defined as a change in soil properties, vegetation or climate that causes a long-term loss of ecosystem services required for sustaining life.The ongoing destabilization of diverse ecosystems may jeopardize the ecosystem services essential for civilization. The consequences are significant, encompassing reduced agricultural yield, heightened wildfire risks, extreme weather conditions, and, critically, intensified scarcity of freshwater resources. (Bradshaw, 2016)

,To accurately study and evaluate the energy requirements of these processes, specific thermal and dynamic indicators are relied upon, such as the Moisture Harvest Index (MHI), which reflects the ratio of the latent heat of condensation to the total heat removed during the process. Furthermore, performance metrics such as water specific production (SWP), recovery ratio (RR), and specific energy consumption (SEC) are prepared Essential for assessing system efficiency. The specific energy consumption in direct cooling systems is expressed mathematically by the following equation:

$$SEC = \frac{Q_{cond}}{m_{H_2O}} \approx C_p \left(\frac{\epsilon_T}{\epsilon_d}\right)\left(\frac{T_i - T_{cond}}{d_i - d_{cond}}\right) + h_{ig}$$

To address the challenges of poor performance in dry and hot climates, some studies have been conducted to develop solar-powered sorbents. For example, porous nanocarbon derived from MAF-4 has an adsorption capacity of up to 306 mg/g at 40% relative humidity with a better water release rate due to its high solar absorption efficiency (97%). But still there is a pressing need to develop and adapt traditional mechanical systems to the environmental conditions Harsh in semi-arid areas by practical structural, design and operational improvements (Feng *et al.*, 2024) (Tu *et al.*, 2018) (Kannan *et al.*, 2017) (Gonçalves *et al.*, 2016)

Based on this research gap, this research aims to study and evaluate the performance of an innovative portable and easy to move to direct cooling system harvest water from the atmosphere, it was designed and field-tested in the dry climatic conditions of Karbala, Iraq (during May and June 2026). As described in the system reference design such as figure (1-1) the device relies on independent operation via a solar panel and battery and uses a small 1/6 HP (Small Refrigerator Compressor) compressor Coupled with a condenser grid to cool the air. The ambient air is drawn and propelled by a fan through a tube containing a silicone rubber

heater, which then passes through the dehumidification tank with a perforated tube (Perforated tube) To increase condensing efficiency.

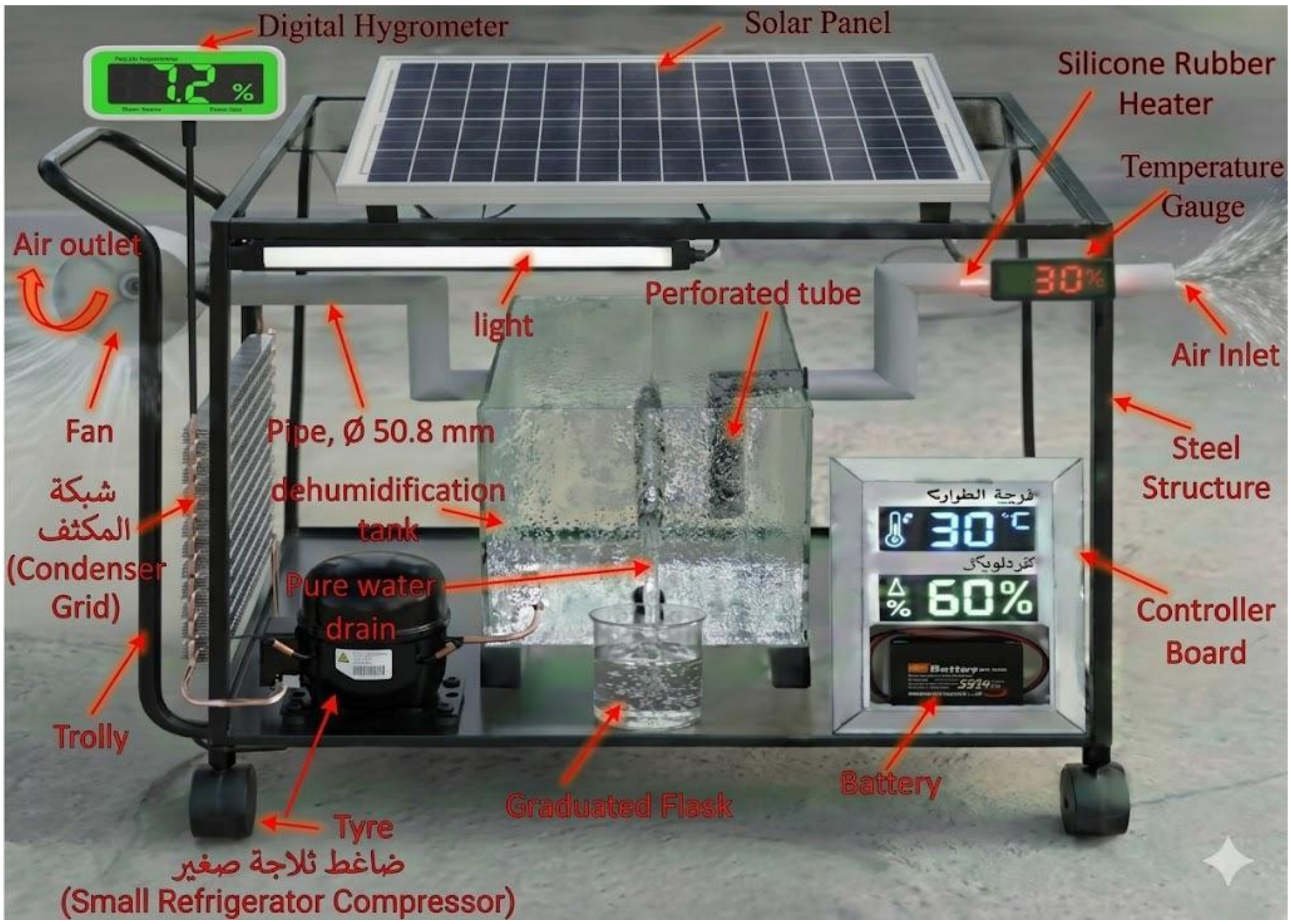

Figure 2-: Diagram of the device's components

The objective of the study is to analyze the influence of structural and climatic additives on the total productivity of the system. The experiments performed are a comparison of the baseline performance (without additives) with a wire screen mesh incorporated in the humidifier and the use of a fog generator to modify the inlet air characteristics. Field tests showed that productivity varied greatly with operating conditions and the system attained a maximum throughput of 140 ml It shows the efficiency of direct cooling systems to work efficiently in hot and dry environments when combined with the fog generator and the metal grid at optimal air speeds of 0.65 m/s.

2. EXPERIMENTAL WORK

The Experimental Atmospheric Water Harvesting System (AWH) **was** designed and manufactured locally to operate under the climatic conditions of Iraq. As shown in Figure 2, the system is fully mounted on a movable metal structure (cart) to facilitat**e** field inspections. The mechanical compression cooling system is the heart of the system, as it is powered by a 1/6 HP compressor. The cooling coil (evaporator) is placed inside a tank Iron-coated humidifier with several pigments and a layer of antibacterial dyes, while the condenser mesh was left exposed to the surrounding environment to release and dissipate heat outward

The air handling unit consists of a network of plastic pipes (PVC) with an outer diameter of 50.8 mm. At the air outlet an intake fan sucks the ambient air into the system. The incoming air passes through a silicone rubber heater with a thermometer to accurately control and simulate the felt heat conditions. The wet air is then pumped into the humidification tank via a perforated tube to ensure that it is regularly distributed to the cooling coil. Condensation occurs when the air temperature drops below Dew point, collected water collected through a pure drainage pipe in a stepped flask. To ensure the sustainability of the business, an independent (off-grid) power supply system consisting of a solar panel, a storage battery has been integrated to make the device work in various conditions and does not require a national electricity bill, as well as a digital control panel with an emergency locking system, temperature and humidity sensors, fan speed control, and more.

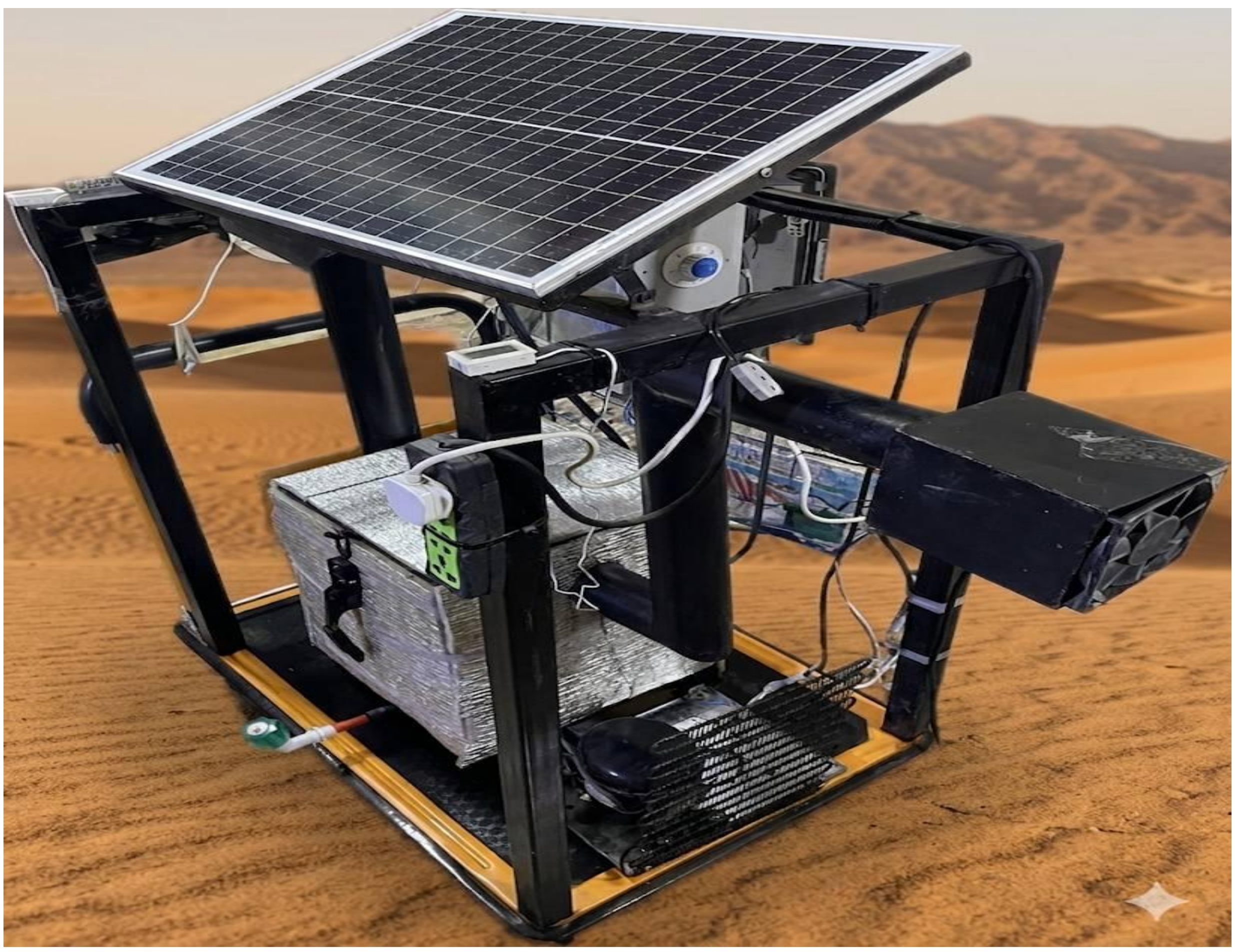

Figure. 3-: Pictorial view of the experimental rig structure.

3. Measuring Instruments

3.1 The thermodynamic performance of the system is accurately monitored by several reliable measuring devices:

3.2 Ambient air temperature, temperature of the air inside the tank, temperature of the tank wall and surface temperature of the coolant coil were continuously recorded using K-type digital thermocouples (±0.5°C accuracy).

3.3 Relative humidity: Digital humidity meters (±2% accuracy) are installed at the inlet air and inside the dehumidification chamber to measure the change of vapor content.

3.4 Air Speed: Measure and control the wet air velocity using a digital anemometer (0.±1 m/s accuracy).Water Yield**:** Use a standard amplified laboratory decanter (with an accuracy of ±1 ml) to measure the cumulative volume of condensed water

3.5 Microcontroller-based system used to automate the condensing process. It shall read data from temperature and humidity sensors and actuate a 12V DC fan and/or a silicon heater as predetermined thresholds

Figure. 4-: Temperature Gauge TBM-10

Figure 5- . Humidity Meter

Figure. 5-: (digital animator) smart sensor ST8816

Figure. 6-:Controller – LIVETECH Zl-7928A

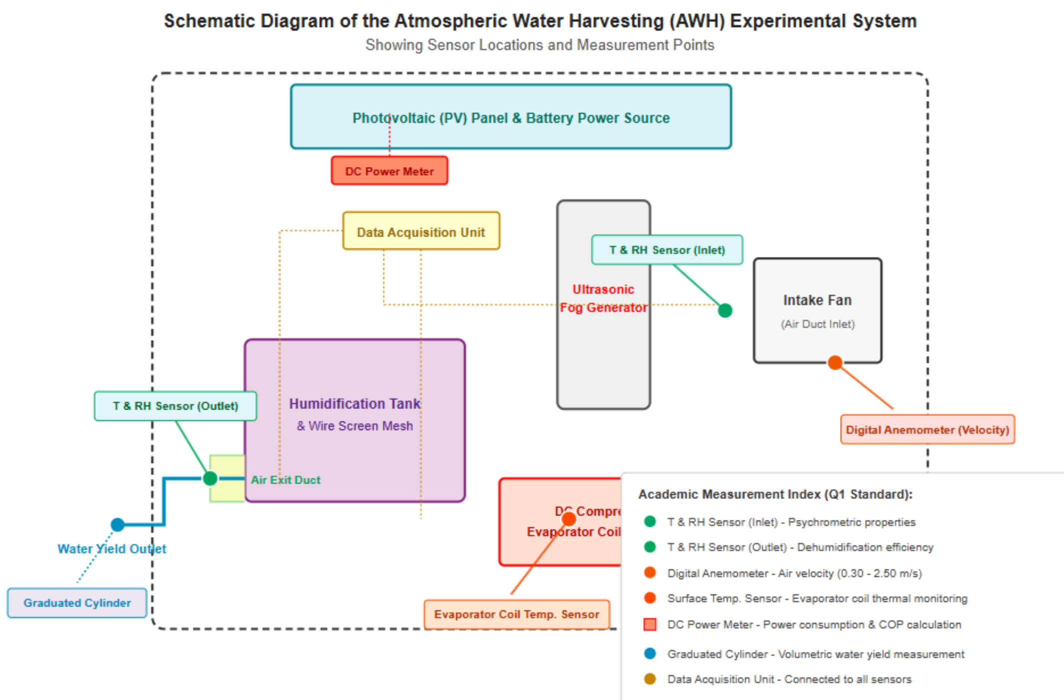

Figure 7 The detailed geometric diagram shows the locations of the sensors and units of measurement in the AWH system.

4. EXPERIMENT PROCEDURE

To assess the performance of the proposed atmospheric water harvesting (AWH) system under controlled operating conditions, an experimental study was carried out over several experimental days in the months of. The system was run for about 15–20 min before each experimental run in order to reach steady-state thermal conditions. The evaporator surface temperature was maintained at 3–5°C for this period to stabilize the thermal performance for the following data collection.

Most experiments were carried out at night (12:00 a.m.–5:00 a.m.) to benefit from the naturally higher ambient relative humidity, which favors condensation. Each experiment lasted 5 h, and then the accumulated water yield was measured. Only for comparative evaluation of daytime and nighttime system performance were additional daytime experiments (12:00 p.m. to 5:00 p.m.) performed.

The experimental program was structured in four operational phases to systematically examine the effect of various condensation enhancement techniques:

Phase I: Initial setup

The system was run as designed, with no devices for enhancement of condensation. Baseline water yield was measured at inlet air velocities of 0.65, 0.75 and 0.83 m/s and the optimum air velocity was found within the range investigated.

Phase II: Adding the Wire Mesh

In the humidification chamber, a stainless steel wire mesh was installed in the inside to improve the performance of condensation. The wire mesh increased the effective heat transfer surface area, creating additional nucleation sites for droplet formation and causing local airflow disturbance, which resulted in better vapor-surface interaction and condensate formation.

Phase III: using ultrasonic fogger

An ultrasonic fogger was placed in the inlet air flow path to increase moisture content of incoming air to simulate atmospheric conditions of high humidity. We used the same setup to test the influence of higher absolute humidity on the water yield and the overall condensation performance of the system.

Phase IV Integrate the fog generator with the grid

The system was operated simultaneously with the ultrasonic fog generator and the wire mesh to observe the combined effect on the water production. The comparative tests were conducted at optimum inlet air velocity of 0.65 m/s, in both day (12:00 p.m.–5:00 p.m.) and night (12:00 a.m.–5:00 a.m.). Additional validation experiments were conducted under controlled environmental conditions with an ambient relative humidity of around 70% and an ambient temperature of around 34°C.
The hybrid configuration demonstrated the best performance among all the tested operating conditions, and obtained a maximum water yield of 140 mL during the nighttime operating period at the optimum inlet air velocity of 0.65 m/s

5. RESULTS AND DISCUSSION

- **Effect of inlet air velocity**

The effect of incoming air velocity on system performance was studied using three air speeds of 0.65 & 0.75 and 0.83 m/s, with all other operational variables installed to ensure that the airspeed effect was isolated.

Experimental results showed that the air velocity of 0.65 m/s achieved the highest water productivity. The amount of produced water was reduced gradually when the air velocity increased from 0.75 m/s to 0.83 m/s. This behavior is due to the shorter dwell time of moist air on the surface of the evaporator at higher speeds, which limits the heat transfer, condensation and droplet growth. Accordingly, the inlet air velocity of 0.65 m/s is the best operating speed of the system under the experimental conditions conducted in this study

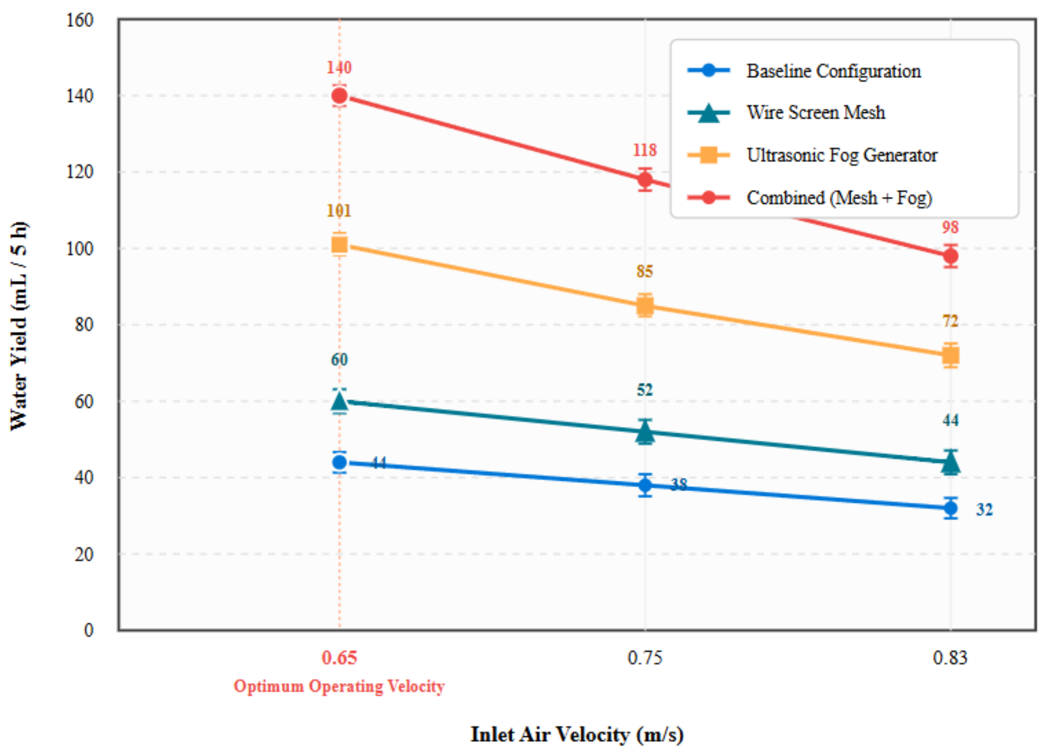

Figure 9 shows the effect of air speed on productivity and shows that 0.65 m/s is the best speed

- **Operating without any add-ons**

The experimental evaluation of the Atmospheric Water Recovery (AWH) system was carried out for a standard five-hour operating period. The basic system without any additions or improvements reached a reference production of 44 ml of water.

- **Adding the wired mesh**

The integration of the wire mesh increased the amount of water produced to 60 ml, achieving an increase of 36.4% compared to the base condition. This improvement was due to the increase in the effective condensing surface area and the provision of additional locations for the start of the droplet condensation, which contributed to improve the formation and aggregation of droplets on the cooled surface. As shown in Figure 8, which presents the temporal comparison of the evolution of cumulative water production and relative humidity between the wired grid system and the base state, recording an overall improvement of 36.4%.

- **Ultrasonic Fog Machine**

When the ultrasonic mist generator is used by itself, it produces as much as 101 ml of water. This is due to the fact that the highly fine water spray increases the humidity of the incoming air, which increases the amount of condensable water vapor reaching the surface of the evaporator, and thereby enhances the condensation process.

- **Integrated operation (fogger and wire mesh in one unit)**

The maximum water yield of 140 ml was observed by the simultaneous operation of the wire mesh and ultrasonic mist generator, which was 218.2% higher than the baseline. The result points to a synergistic effect between increasing the effective condensation surface area and increasing the moisture content of the incoming air, which improved the condensation process and increased the water productivity under the operating conditions used in this work

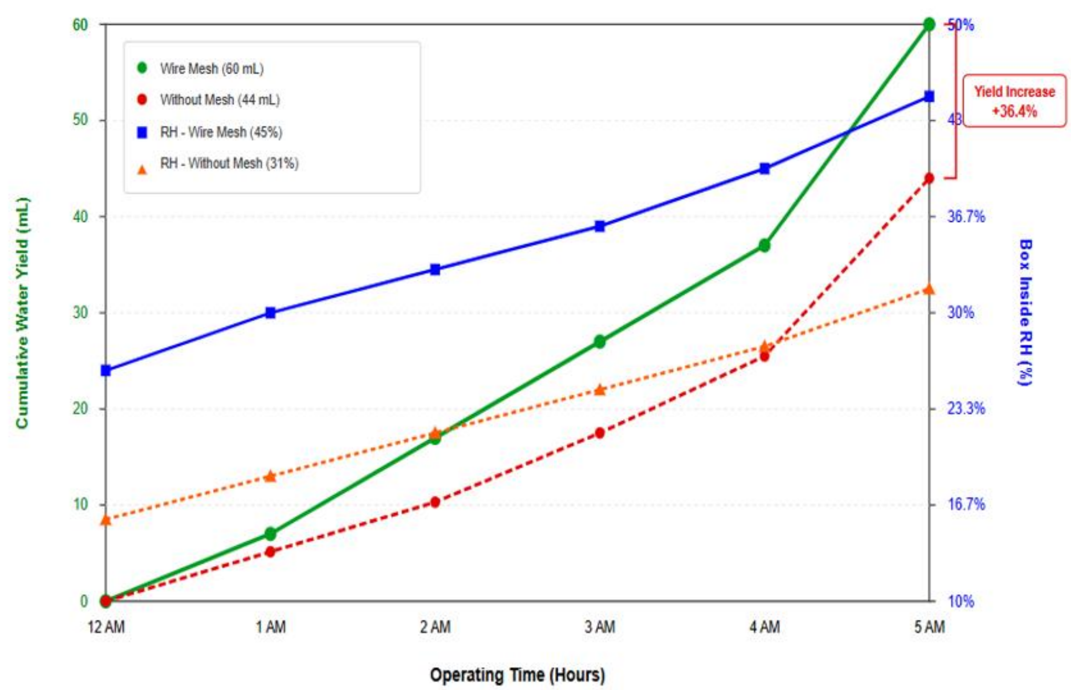

Figure 8 The graph shows the temporal comparison of the evolution of cumulative water and relative humidity production between the wired grid system and the base state, recording an overall improvement of 36.4%

6. Energy Consumption Analysis

The system is based on an independent power module consisting of a solar panel and a 70 V (840 Wh) battery and an electric inverter to power the compressor and fans. Electrical measurements showed that the compressor's operating current stabilized at about 1.5 A on the inverter's output during stable operation. Experiments also proved that the battery capacity was sufficient to power the system for 5 hours during night operation, while the solar panel recharged the battery during daylight hours, confirming the possibility Operating the system independently of the electricity grid in field applications and remote areas.

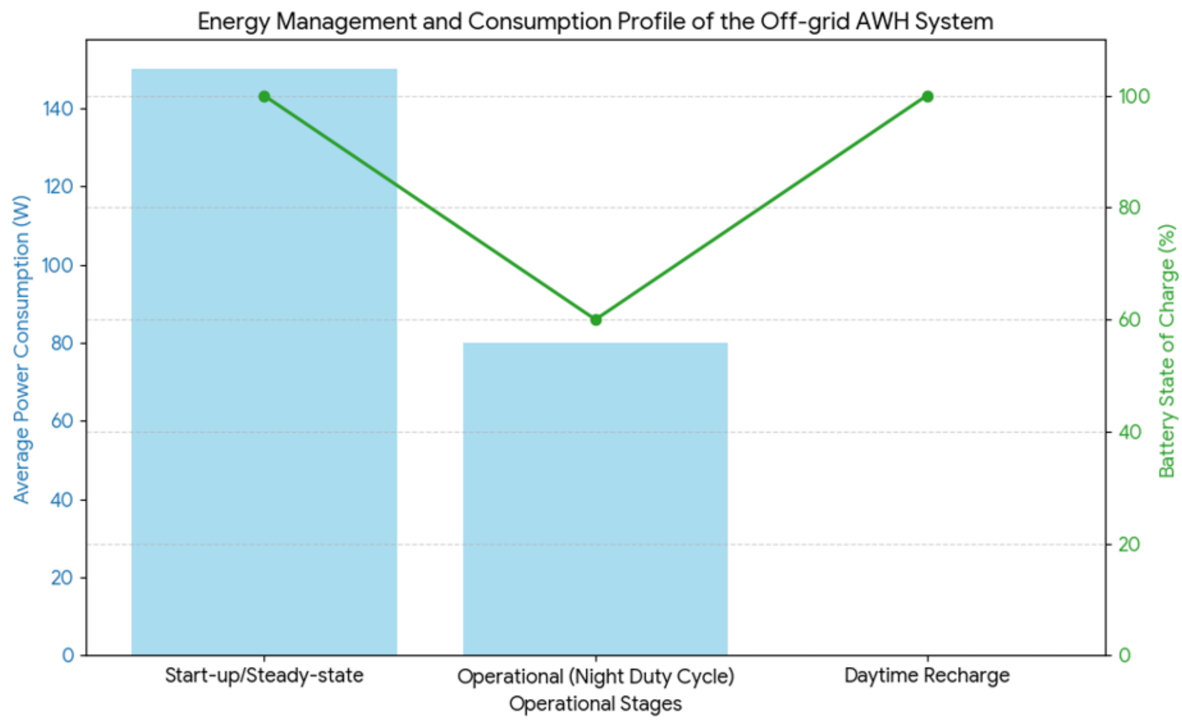

Figure 7. Energy consumption profile and battery state of charge (SOC) dynamics across different operational stages of the off-grid AWH system.

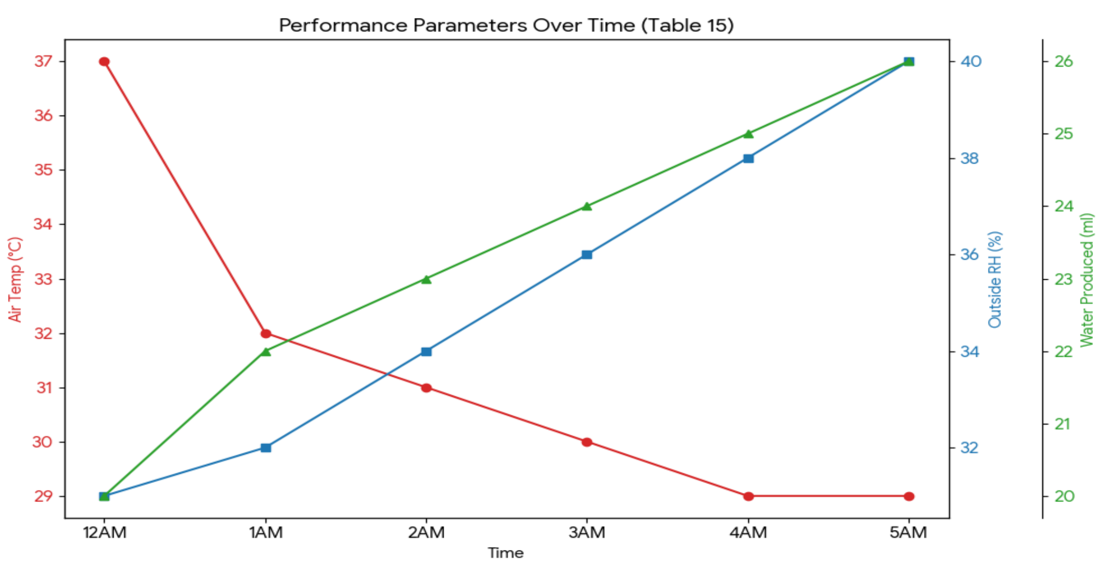

Figure 3. Variation of air temperature, outside relative humidity, and cumulative water production over the experimental time period.

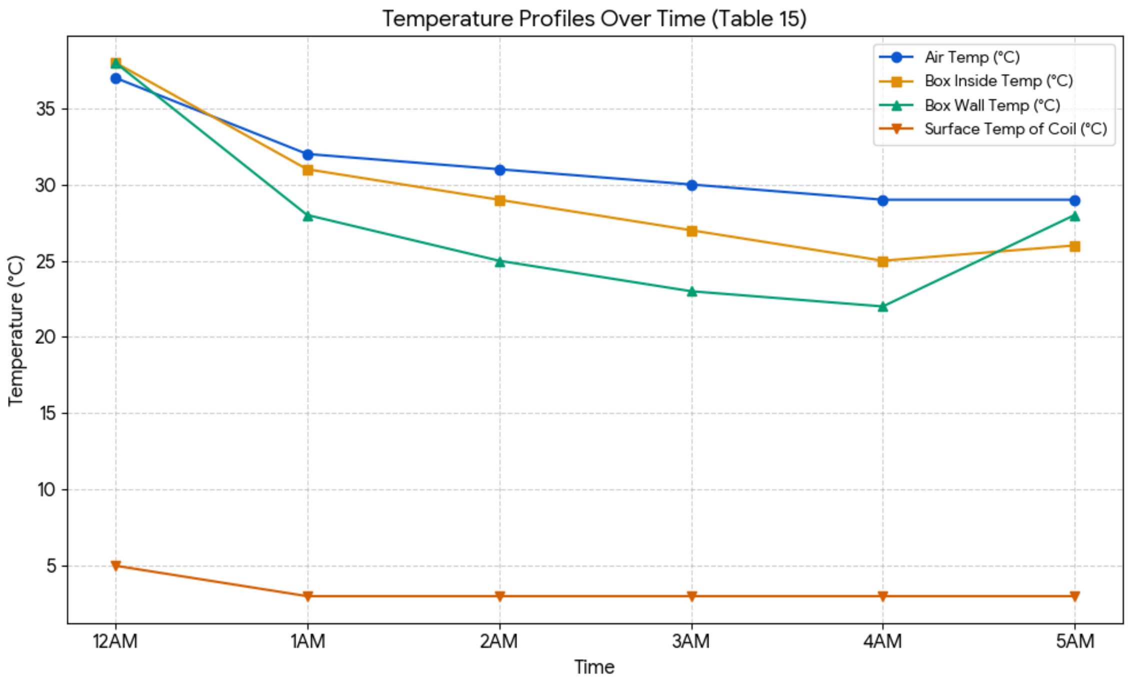

Figure 4. Comparison of the total cumulative water production across different system configurations and operating airflow velocities

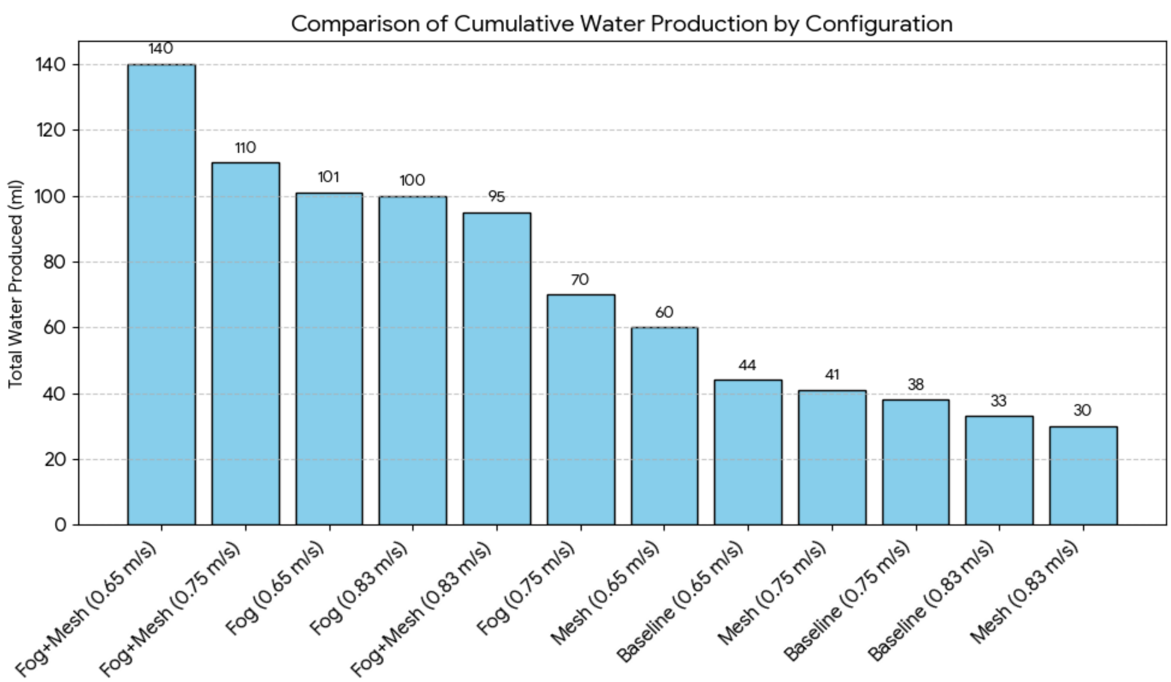

Figure 5. Temporal evolution of air, box interior, box wall, and cooling coil surface temperatures throughout the experimental duration

7. Cost Analysis for AWH System

The nature of the water harvesting system from the air and its components with all its accessories is one of the prerequisites in economic feasibility calculations and cost analysis. Therefore, the cost estimate is made based on fixed costs and variable costs. The table below shows the detailed components of the system and its estimated cost. Based on the life span of the system and the daily production rate, the cost of producing one liter of the system can be determined using the following equation:

$$C = F + V$$

It represents the C Annual total cost, the F fixed cost, and the V variable cost.

To facilitate and achieve the process of calculating the cost accurately, the following requirements and assumptions have been taken into account:

1. The lifespan of the system is five years.
2. The system operates at an average of 325 days a year.
3. Variable cost is equal to 0.3 of the fixed cost per year, which includes regular maintenance (e.g. metal mesh replacement, battery maintenance, dehumidification tank cleaning AWH
4. **System Calculation**

Based on the combined parts of the system, the fixed cost is, and therefore from the equation above: $F = 225\$$

$$C = 225 + (0.3 \times 225 \times 5) = 562.5\$$$

Referring to the experimental data of the system in optimal operating conditions (when the fog generator is combined with the metal grid, the production reached 140 ml within a 5-hour measurement period. Assuming the system is operated at a similar efficiency for 10 hours per day, the average daily output is approximately 0.28 l/day. In the scorching summer

Accordingly, the total expected production during the life of the system is calculated as follows:

$$0.28 \times 325 \times 5 = 455\ Liters$$

Consequently, the cost of producing one liter of the system amounts:

$$\frac{562.5}{455} = 1.23\$$$

Table 1: Design Cost of System Components

Item	Estimated Cost ($)
Steel Structure, Trolly & Tire	35.00
Small Refrigerator Compressor & Condenser Grid	65.00
Solar Panel and Battery	45.00
Humidification Tank	15.00
Pipe, Ø 50.8 mm & Perforated tube	8.00
Controller Board and Measuring Devices (Digital Hygrometer, Temperature Gauge)	20.00

Silicone Rubber Heater and Fan	12.00
Fog Generator and Wire screen mesh	15.00
Other accessories (lamp, flask insert, drain outlet, silicone) (Auxiliaries: light, graduated flask, drain, etc.)	10.00
Total fixed cost	**225.00**

8. CONCLUSION

This study presented the design, manufacture and experimental evaluation of a solar-powered atmospheric water harvesting system AWH based on a direct cooling cycle to operate in dry climatic conditions in Karbala city, Iraq. The main findings are summarized as follows .

- **Without any enhancers** The conventional configuration of direct cooling showed limited water productivity in low humidity conditions, achieving a reference water productivity of 5 hours of operation. This result highlights the limited performance of independent steam compression$44\ mL$ systems AWH in dry environments.
- **Wire mesh effect:** The incorporation of the wire mesh into the condensing chamber increased the production of water to, by providing additional effective surface area for condensation and promoting the shedding and discharge of condensed droplets$60\ mL$.
- **Effect of the fog generator:** The ultrasonic fog generator contributed to the significant improvement of system performance by increasing the humidity of the incoming air, which raised the productivity to the point of increasing the inlet air humidification, demonstrating the critical importance of humidification of the inlet air in enhancing condensation efficiency$101\ mL$.
- **Synergistic effect (network + mist):** The simultaneous operation of the wire mesh and the fog generator achieved the highest water experimental outcome reached, and with an increase in its value compared to the basic reference configuration. This result confirms the positive syntactic effect resulting from the combination of optimization of condensation surfaces and the humidification of the incoming air$140\ mL 218\%$.
- **Optimal air velocity**: Among the tested air velocities 0.65 and, 0.75 & $0.83\ m/s$ the optimal operating condition was achieved at a speed where the balance between $0.65\ m/s$heat transfer, mass and air dwell time achieved maximum water productivity. Increasing the speed above this limit reduced productivity due to the reduced air retention time on the evaporator surface.
- **Night and day performance:** Under optimal operating conditions, the system recorded a nighttime output of as compared to during daytime operation, reflecting the positive effect of low ambient temperatures and high relative humidity at night on condensing efficiency$139\ mL 120\ mL$.
- **Energy and economic feasibility:** The experimental results demonstrated the ability of the proposed photovoltaic system to operate completely independently of the electricity grid during the test period, $5\ hours$demonstrating the technical feasibility of decentralized freshwater production in arid and remote areas. Although the current cost of production is still higher compared to traditional large-scale water supply technologies, the prototype provides a practical platform that can be scaled up in the future through improved heat transfer technologies and scale expansion Operational of the system.
- **General Conclusion:**

This study shows that the integration of inlet air humidification technology with the optimization of condensing surfaces represents an effective approach to raise the performance of direct cooling aerial water harvesting systems in hot and dry climates.

9. Recommendations

Based on the findings of this study, the following concise recommendations are proposed for future optimization and development of AWH systems:

1- **Advanced Condensing Surface Materials:** Apply nanoparticle surface coatings (hybrid superhydrophilic/superhydrophobic patterns) on the wire mesh to accelerate micro-droplet coalescence, reduce thermal film resistance, and facilitate rapid gravity-driven drainage.

2- **Automated Control & Scheduling:** Implement IoT/PLC-based automated controllers to maintain optimal airflow velocity ($0.65\ m/s$) and coil temperature ($3 - -5\ ^{\circ}C$) during nocturnal operating windows ($00{:}\ 00\ to\ 05{:}\ 00\ AM$).

3- **Operational Capacity Expansion & Solar Integration:** Pair future AWH units with solar photovoltaic (PV) systems to increase operational capacity and extend running periods across longer daily hours, enabling continuous and sustainable off-grid water production.

4- **Utilization of Metal-Organic Frameworks (MOFs):** Explore the integration of porous Metal-Organic Frameworks (MOFs) within the air-intake channel to adsorb moisture under hyper-arid daytime conditions, followed by thermal desorption using low-grade solar heat to achieve continuous water extraction.

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