Water Generation from Ambient Air Using Blue Silica Gel

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Abstract— **This project explores an advanced method for water harvesting by using silica gel as a sorbent to draw water from atmospheric humidity. The main goal is to create and develop a prototype that can generate one liter of water daily.**

The prototype leverages silica gel for its excellent adsorption capacity, as well as its affordability and availability. The system consists of two chambers: the first is the sorbent unit that contains the silica gel, the second one is the condenser made from acrylic.

The system operates through a three-stage process: adsorption, desorption and condensation. At the adsorption stage, silica gel captures water vapor from fresh air. During the desorption phase, trapped water vapor is released through heating with a heater and extracted through a fan to the condenser. At the condensation phase, water vapor condenses through free cooling. The prototype works 8 cycles a day, producing approximately 355.2 milliliter per day, and one kg of silica sorbent produces 142.0 milliliter per day.

Keywords - Water harvesting, vapor adsorption, water from ambient air, silica gel

I. INTRODUCTION

Water scarcity remains a critical global challenge, with only 2.5% of Earth's water resources classified as freshwater, yet required to sustain a projected population of 9.7 billion by 2050 [1]. This crisis is exacerbated by pollution, climate change, and unsustainable consumption patterns. For instance, global water demand has surged six fold over the past century, outpacing population growth [2]. In Palestine, renewable water resources are estimated at 650 million m³/year, but overexploitation of groundwater (80% of total consumption) and political constraints have intensified shortages, reducing per capita consumption to 130 liters/day—below the global average of 150 liters/day [3,4].

Energy insecurity further complicates Palestine's resilience. Over 90% of electricity is imported, while local demand exceeds 1,300 MW [5]. While solar energy holds long-term potential, the current prototype uses electric heating for desorption. Future work can integrate solar photovoltaic (PV) and solar collector systems to reduce operational costs and enhance sustainability.

Atmospheric Water Harvesting (AWH) Methods are broadly categorized into three approaches: condensation involving cooling air below dew point, fog harvesting which is capturing airborne droplets via mesh/bio-inspired nets, and sorption which is moisture capture using hygroscopic materials. While condensation and fog harvesting are limited by energy demands or climatic constraints, sorption-based AWH (SAWH) offers versatility for arid regions like Palestine.

II. SORPTION-BASED ATMOSPHERIC WATER HARVESTING

SAWH relies on adsorbents to capture atmospheric moisture, followed by thermal desorption. The process involves three phases; Adsorption: where water vapor binds to the sorbent's porous structure. Desorption: where the sorbent is heated to 90°C that releases trapped moisture as vapor. Condensation as vapor liquefies into potable water [6].

Material to be used for sorbents should have high adsorption capacity (>10% at low relative humidity RH), low regeneration energy (<100 kJ/mol), and cost-effectiveness and reusability [6].

While advanced materials like MOFs achieve higher capacities (e.g., MOF-801: 0.25 g/g), silica gel was selected for this project due to:

1. Moderate Performance: 20% adsorption at 50% RH, sufficient for Palestine's climate [7].
2. Low-Cost & Availability:10 times cheaper than MOFs and locally accessible.
3. Durability: Stable across 3,000+ cycles with minimal efficiency loss (<5%) [19].

III. DESIGN OF PROTOTYPE UNIT

Design of prototype is based on the ambient weather conditions for Ramallah obtained from the official ministry of transport website and given in table I for months May to September including the average relative humidity, maximum temperature, minimum temperature and sunlight hours [8]. The design assumptions include values given in table II.

Table I Average weather conditions in Ramallah

Element	May	June	July	August	September	Average value
Average relative humidity %	57.7	62.8	63	74	72.4	66
Average max temperature ℃	24.7	26.9	28.4	28.7	27.2	27.2
Average min temperature ℃	15.9	18.1	19.6	19.8	13.6	17.4
Sunlight hours	10.5	11.9	12	11.3	9.9	11.12

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Table II List of Assumptions for Prototype

Parameters	Value
Minimum humidity	66%
Average max temperature ºC	27.2
Average min temperature ºC	17.4
Daily water production	1 liter
Average daily sunlight hours	11.12
Average daily absence of sunlight	12.88
Captured water per mass of the sorbent (ω_{cap})	0.2

A. *Adsorption Phase*

The fan with air flow rate of 37.2 m^3/h was chosen and used for this design, hence it was available.

Thus $\dot{m}_{air} = 0.012\ kg/s$

To calculate the humidity ratio (w_2) at T_2 this equation was used:

$$\dot{m}_{mois} = \dot{m}_{air} \times (w_{amb} - w_2) \qquad (1)$$

$\dot{m}_{mois}$: masses of the moisture [kg]

$\dot{m}_{air}$: masses of the air [kg]

w_2: Humidity ratio at T_2

w_{amb}: Humidity ratio at T_1

The captured water flow rate value was derived from reference [9] as shown in figure 1.

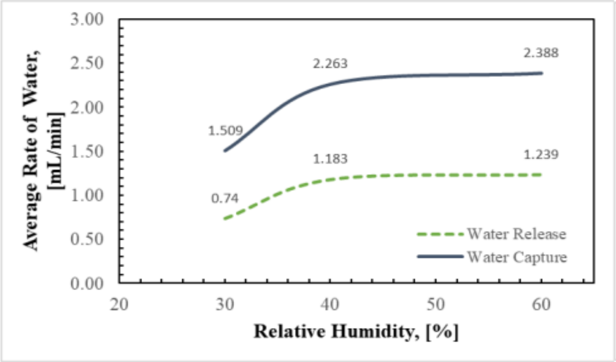

Figure 1 Rate of water versus relative humidity for blue silica

At relative humidity 57.7% the average rate of water 2.388 mL/min, equivalent to $\dot{m}_{mois}= 3.98 * 10^{-5}\ L/s$, also from the psychrometric chart at $T_1 = 25$ ℃ $w_{amb} = 0.131$

Using equation1 gives $w_2 = 8.08 * 10^{-3}$, from the psychrometric chart the relative humidity = 41% at the same temperature (T= 25 C).

B. *Condensation Design*

To calculate the temperature at dew point:

From the psychrometric chart at $\emptyset = 41\%\ and\ T = 60$℃

Where T= 60 ℃ is found experimentally

$T_{dew} = 41$ ℃

Using equation 2, the area of condenser was calculated:

$$Ac = \frac{m_{sorb}}{\int_0^{2hours} h(Tc - Tamb)dt} \left[(T_a - T_{dew})(\omega_{cap}CP_w) + \omega_{cap}h_{fg}\right] \qquad (2)$$

Assuming condensation time is 2 hours with h_{fg}=2358 kJ/kg, h=0.01 kW/m^2. K, and Cp=4.186 kJ/ kg.K , the condenser area is $Ac = 1.272981412\ m^2$

The condenser was in the shape of a cube and to be attached to absorber exit, so the length of the side x was calculated using equation 3

$$Area = 0.45 * 2x + 0.41 * 2x + 0.41 * 0.49 \qquad (3)$$

$X = 60\ cm$

C. *Sorbent Design*

To calculate the volume for silica gel:

Assuming the weight of silica is 2.5 kg.

$$V = \frac{M}{Bulk\ density} \qquad (4)$$

V: Volume of Silica gel

M: Mass of silica gel

$$V = \frac{2.5}{720} = 3472\ cm^3$$

The area of the shelf on which silica is placed was calculated:

$$A = \frac{V}{thickness} \qquad (5)$$

A: Area of shelf

V: Volume of silica gel

Shelf thickness (assume 3 mm)

$$Area = \frac{3472}{0.3} = 11574\ cm^2$$

We have 8 shelves so

$$Area\ for\ one\ shelf = \frac{11574}{8} = 1446.74\ cm^2$$

$\sqrt{1446.74} = 38.03\ cm$

0.3125kg of silica gel will be placed on each shelf.

D. *Heater Calculation*

Based on sorbent and heat of 50 kJ/mole and 0.2 moist removal

$$q_{latent} = q_{st} * w = 50 * 0.2 = 10 \frac{kJ}{mole} \qquad (6)$$

$weight = number\ of\ moles * moleculer\ weight$

$number\ of\ moles = 41\ mole$.

Where:

Weight = 2500 gram, and Molecular weight = 60 g/mole, then

$$q_{latent} = 41 * 10 = 413\ kJ$$

Assuming 10 minutes as heating period

$$power = \frac{413}{10 * 60} \approx 700\ Watt$$

Two 700-watt heater element was selected to accelerate the rise in temperature to 90 Celsius were the silica start to release the water vapor.

IV. TESTING OF PROTOTYPE UNIT

Prototype of the water from ambient air unit using silica gel as absorbent is shown in figure 2

Figure 2 Final Prototype

The prototype includes two main chambers: a sorbent unit containing silica gel and a condenser chamber. Initially, the fan was positioned at the inlet to push air into the sorbent unit but was subsequently moved to the outlet side to enhance vapor extraction efficiency. The condenser chamber is sealed with a wooden door, while the sorbent unit is insulated to minimize heat losses. During operation, silica gel shelves initially adsorb moisture from ambient air. After adsorption, these shelves are placed inside the insulated sorbent unit and heated to release the trapped water vapor.

However, due to uneven heating observed in initial experiments, a notable temperature gradient occurred between the top and bottom shelves; when the top shelf reached 90°C, the bottom shelf was only at about 60°C. To resolve this issue and ensure uniform heating and efficient vapor release, a temperature sensor was installed on the bottom shelf. This sensor activates the fan once the bottom shelf reaches 60°C, and continues operation until five minutes after the temperature reaches 90°C, effectively transferring released vapor to the acrylic condenser. This controlled heating strategy ensures uniform desorption across all silica shelves. This cycle is repeated eight times daily

V. RESULTS AND DISCUSSION

To evaluate the effectiveness of the designed prototype, three experimental trials were conducted under controlled environmental conditions. The results showed a clear progression in system performance as design modifications were implemented between tests. Key evaluation criteria included the quantity of condensed water, thermal efficiency, and overall system performance.

A. Experiment 1: Initial Prototype Trial

The first experiment, conducted on January 15, 2025, resulted in a relatively low water yield of 69.5 mL. Although the release efficiency was high at 88%, the condenser efficiency reached only 22%, leading to an overall system efficiency of 19%. Major losses were attributed to vapor leakage from unsealed joints in the condenser and the flexible duct. Furthermore, the temperature sensor was initially placed on the fifth shelf of the sorbent unit, which led to non-uniform heating—particularly in the lower shelves—causing uneven desorption of water from the silica gel. These observations highlighted the importance of heat distribution and system insulation in optimizing water recovery.

B. Experiment 2: Improved Sealing and Layout Adjustment

In response to the issues identified in the first test, the prototype was modified by sealing all system openings and repositioning the condenser to align directly with the sorbent unit, minimizing flow resistance. The temperature sensor was also relocated to the third shelf to better reflect the average heating conditions across the silica trays. As a result, water output slightly increased to 75 mL. However, the overall efficiency dropped to 17.3% due to a malfunction in the extraction fan during the desorption phase, which limited vapor transfer to the condenser. This experiment emphasized the critical role of stable airflow and fan reliability in system operation, in addition to thermal considerations

C. Experiment 3: Optimized Control and Sensor Placement

The third trial incorporated further improvements, including repositioning the temperature sensor to the first shelf (at the bottom of the sorbent unit) and integrating automated fan control based on temperature feedback Figure 3 shows the sorbent temperature, condenser temperature and condenser relative humidity as function of time during experiment 3. Summary of three experiments results is given in table III.

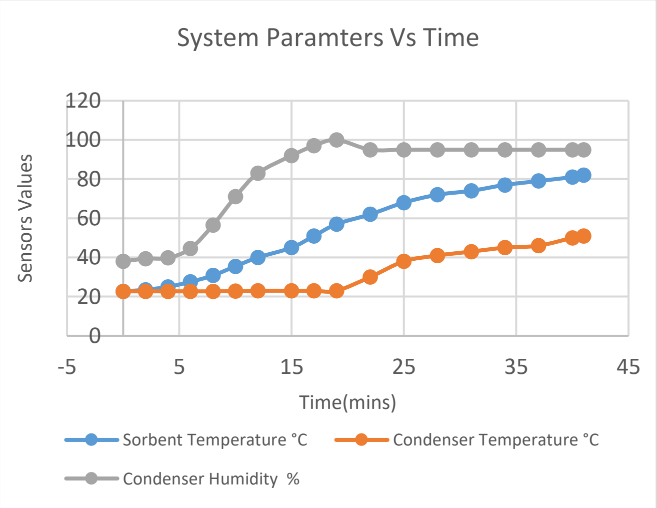

Figure 3 Variation of temperature and humidity with time in Experiment 3

These enhancements resulted in the best performance across all metrics, with 80 mL of water condensed and an overall efficiency of 24%. The condenser efficiency notably improved to 31.1%, while release efficiency stabilized at 77%. Visual inspection of the silica trays confirmed thermal uniformity; Shelf 6 at the top was fully desorbed (indicated by a complete blue color), whereas Shelf 1, located at the bottom, had shown incomplete desorption in earlier tests, see figure 4. This validated the need for bottom-up thermal control to ensure all levels of silica reach the target temperature for effective vapor release

Table III A comparative summary of the three experiments

Experiment #	Condensed Water (mL)	Release Efficiency (%)	Condenser Efficiency (%)	Overall Efficiency (%)
1	69.5	88	22	19
2	75	74	23.4	17.3
3	80	77	31.1	24

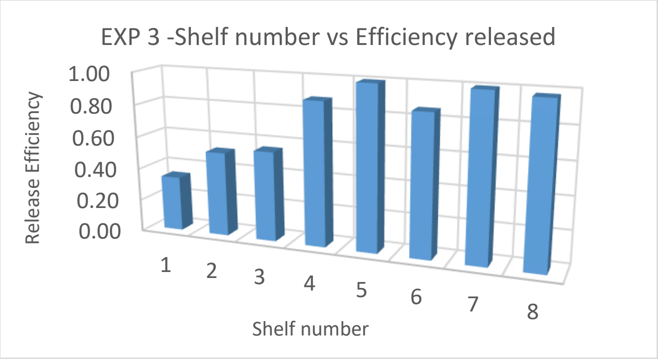

Figure 4Water release efficiency per shelf in Experiment 3

D. *Water Quality Assessment*

The water collected from the final experiment was analyzed at Birzeit University's laboratory to assess its suitability for human consumption. The results indicated a TDS level of 382 mg/L, which falls within the acceptable range for drinking water (300–600 mg/L). The pH was measured at 8.84, suggesting slightly basic water that is safe but may produce a mild metallic taste. Microbial analysis revealed a Total Aerobic Count (TAC) of 85 CFU/100 mL and a Total Coliform count of 3 CFU/100 mL, both within acceptable thresholds. Fecal coliforms were absent, indicating no biological contamination. These values collectively confirm that the extracted water is safe for drinking and domestic use. These findings underline the importance of three key factors in optimizing sorption-based atmospheric water harvesting: (1) precise thermal control via sensor placement, (2) effective sealing and component alignment, and (3) intelligent automation of fan operation. The project demonstrates a clear progression toward an efficient and scalable system suitable for deployment in arid, water-scarce environments.

VI. CONCLUSION & FUTURE WORK

This project demonstrates a scalable, atmospheric water harvesting system tailored to Palestine's arid climate. The final prototype achieved 80 mL/day at 24% overall efficiency, producing potable water compliant with WHO standards (TDS: 382 mg/L, pH: 8.84).

Future work will explore hybrid solar thermal-electric heating and cycle automation. This innovation underscores the potential of adsorption-based technologies to mitigate water scarcity sustainably, emphasizing practicality, scalability, and resilience

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