



Prototype Development of a Two-Stage Hydrogel–CaCl₂ Absorption–Desorption Device for Atmospheric Water Harvesting

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Abstract

Freshwater scarcity has become a pressing global challenge, driving the need for innovative and sustainable water production technologies. Atmospheric water harvesting offers a promising solution by exploiting the vast reservoir of water vapor in the air, particularly for arid and remote regions. In this study, we developed a novel two-stage moisture absorption–desorption system using a highly hygroscopic hydrogel–CaCl₂ composite (7.4% hydrogel, 92.6% CaCl₂). The device comprises an absorption compartment equipped with 10 trays (0.675 kg of the composite per tray) for capturing atmospheric moisture and a condensation–recovery compartment integrated with a refrigeration system for efficient desorbed vapor condensation. The system operates in cyclic absorption and thermally driven desorption phases, with each phase offering fully programmable and controllable duration. The desorbed vapor is subsequently directed into a condensation chamber, where it is recovered through an integrated refrigeration unit, and discharged from the system. Experimental results demonstrated a freshwater production capacity of approximately 1 L per day, under air relative humidity of approximately 33%. This integrated approach highlights the potential of hydrogel–salt composites coupled with active condensation for atmospheric water harvesting applications.

Keywords: Absorption–desorption cycles, Atmospheric water, Hydrogel–CaCl₂ composite, Prototype development.

1. Introduction

Freshwater scarcity is a severe global challenge, especially in arid and semi-arid regions where conventional water sources fail to meet growing demands. With only 3 % of Earth's water as freshwater, an estimated 2.8 billion people experience water shortages each year, with projections indicating that two-thirds of the global population may face water stress in near future. Atmospheric water harvesting (AWH), which involves extracting water vapor directly from ambient air, emerges as a promising supplement to traditional water supply methods (An et al., 2022).

AWH systems generally fall into three categories: condensation-based systems that cool air below the dew point, desiccant-based systems using hygroscopic sorbents, and

hybrid or solar-driven systems that combine both mechanisms for improved performance. Desiccant-based systems typically absorb moisture at nights and desorb it using heating cycles, whereas condensation systems actively cool humid air to produce liquid water. Hybrid systems aim to bridge efficiency gaps under varying climate conditions (Li et al., 2018).

Several studies have investigated and developed different AWH technologies in recent years. Lei et al. (2022) introduced polyzwitterionic hydrogels as a promising platform for atmospheric water harvesting (AWH). Exploiting anti-polyelectrolyte effects, the polymer chains interact with hygroscopic salts to trap water vapor and improve swelling behavior, thereby boosting moisture uptake. As a result, the hydrogel

demonstrates outstanding AWH performance, achieving 0.62 g g⁻¹ within 120 minutes at 30% relative humidity, and yielding 5.87 L kg⁻¹ of freshwater per day. Kallenberger and Fröba (2018) developed a calcium chloride–alginate composite sorbent in the form of spherical beads (approximately 2 mm in diameter) capable of absorbing up to 660 kg/m³ of water at 28 °C and 10 mbar vapor pressure, with over 90 % of the absorbed water released at approximately 100 °C.

Lapotin et al. (2021) made a two-stage zeolite-based AWH device utilizing temperature gradients for efficient absorption and desorption cycles. Li et al. (2024) proposed an atmospheric water harvesting (AWH) system based on the “optimal harvesting window” concept, which thermodynamically optimizes absorption temperature relative to ambient humidity. Using silica gel as the sorbent, their prototype achieved daily yields of 5.76–17.64 L with high energy efficiency (0.46–1.5 L kWh⁻¹) under diverse climatic conditions (13–35 °C, 18–72% RH).

When coupled with photovoltaics, the system demonstrated scalable potential, producing 0.66–2 L m⁻² day⁻¹ throughout the year in Shanghai, highlighting “optimal harvesting window” as a promising route toward large-scale, energy-efficient AWH. Min et al. (2023) demonstrated a portable device using a thermoelectric cell to simultaneously provide heating for desorption and cooling for condensation. This system, employing a thermally conductive graphene oxide-doped hydrogel sorbent, achieved high water production rates, representing nearly an order-of-magnitude improvement over traditional designs with equivalent energy input.

Aleid et al. (2022) introduced a zwitterionic hydrogel-based sorbent that utilizes a “salting-in” effect to significantly improve atmospheric water harvesting performance, enabling fully solar-driven freshwater production. In a similar work Du et al. (2025) developed a robust tunable hygroscopic mix-charged polyzwitterionic hydrogel that overcomes the typical trade-off between high moisture absorbency and mechanical strength in atmospheric water harvesting materials.

The novel hydrogel demonstrated exceptional water uptake (2.9 g g⁻¹ at 70% RH) while maintaining remarkable mechanical robustness (225 kPa tensile strength at 200% mass swelling ratio), significantly outperforming conventional zwitterionic polybetaine hydrogels.

Park et al. (2022) introduced a sunlight-activated “sorption ratcheting” strategy using hydrogel sorbents to enhance atmospheric water harvesting. By employing rapid, sequential absorption-desorption cycles activated directly by sunlight, their method achieved an ~80% increase in daily water yield compared to conventional single-cycle systems, while maintaining sustainable operation. This approach optimally leverages the inherent sorption kinetics of hydrogels, offering a scalable solution to improve water productivity in arid regions.

Lee et al. (2025) developed raspberry-like microbeads with nano-/micro-confined polyacrylamide–LiCl hydrogel desiccants to overcome slow sorption kinetics in atmospheric water harvesting. The hierarchical structure, featuring a nanoparticle-rich shell and hydrogel-rich core, shortens diffusion paths and increases surface area, achieving 80% saturation much faster than conventional hydrogels. The material demonstrated stable performance over 16 cycles (13.6 L kg⁻¹ day⁻¹ water release) and was integrated into a solar-driven device yielding 2.39 L m⁻² day⁻¹, offering a scalable solution for rapid atmospheric water harvesting.

While these works show various desiccant and condensation approaches, several persistent limitations remain, including relatively low water production rates, deterioration of sorbent performance over cycles, and inefficient condensation—particularly when relying on passive cooling methods.

The present study proposes a hybrid AWH system that integrates a hydrogel–CaCl₂ composite sorbent with an active refrigeration module. This integrated approach aims to maximize vapor sorption, enable effective vapor desorption, and improve overall water recovery, targeting robust performance under the climatic conditions of low humid regions.

2. Materials and Methods

Calcium chloride (CaCl_2 , industrial grade) and a commercial polyacrylate based superabsorbent polymer (PARS-SAP, Iran) were used to prepare the composite desiccant. A 50 wt % CaCl_2 solution was prepared by dissolving 6.25 kg of salt in 12.5 L of distilled water, to which 500 g of superabsorbent polymer was added and left for 24 h to form a hydrogel. The gel was spread on stainless-steel trays and dried thermally.

A dual-chamber device was constructed consisting of a lower absorption compartment ($55 \times 50 \times 70$ cm) with ten sorbent trays and two 1000 electrical heating elements, and an upper condensation compartment ($30 \times 50 \times 70$ cm) connected via a 60 mm stainless-steel tube. The condensation section

incorporated a vapor-compression refrigeration system ($\frac{1}{4}$ HP compressor, copper coil heat exchanger). The entire assembly was enclosed in a galvanized steel casing insulated with rock wool. A fan (16 W) was provided for the lower compartment to provide air during absorption stage.

A small internal fan was also provided in the lower compartment to circulate air in the system during desorption – condensation stage. An Arduino-based controller regulated fan operation, heaters, and refrigeration. The controller used a 12v power supply, consuming 480 W of electrical power Fig.1 shows a photo and a sketch of the device. The condensed water in the upper chamber directed to a vessel outside the device.

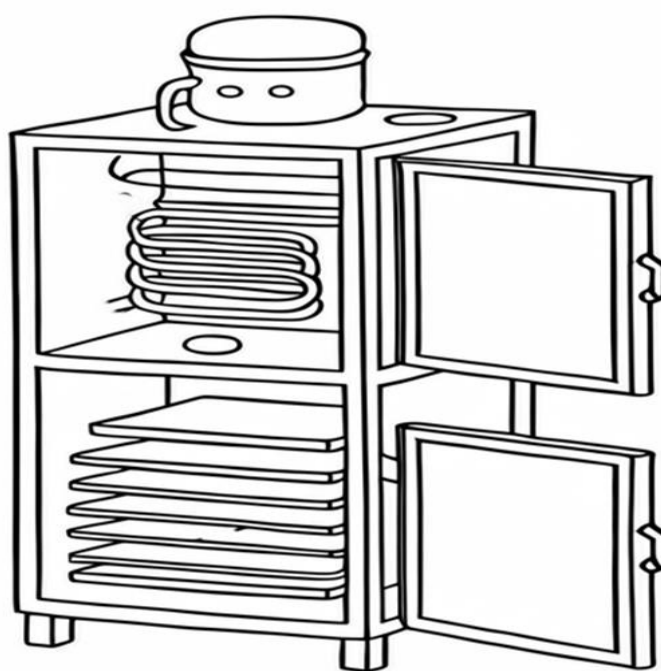


Fig. 1. The photo of the constructed device (left), and a sketch of the device (right)

Operation involved sequential absorption of moisture from ambient air, pre-cooling of the condensation chamber, and thermal desorption of the sorbent to release vapor, which was condensed and collected in the condensation chamber. Performance was evaluated by measuring the volume of water collected per cycle using a graduated cylinder. Ambient temperature and relative humidity were recorded with a hygrometer.

The performance of the device was evaluated under different absorption times (6, 8, 12, and 24 hours) followed by 4 hours of

desorption–condensation at 100°C . Each of the experiments was replicated in three different consecutive days, to ensure the reproducibility of the results.

To compare the performance of the device when loaded with pure CaCl_2 , each of the 10 trays was each filled with 0.7 kg pure CaCl_2 , and similar to the experiments with hydrogel- CaCl_2 , its performance was evaluated under absorption times of 6, 8, 12, and 24 hours followed by 4 hours of desorption–condensation at 100°C . Each of these

experiments was also replicated in three consecutive days.

3. Results and Discussion

3.1. Water harvesting using hydrogel–calcium chloride composite

In a series of absorption experiments conducted over varying durations, the device demonstrated a clear increase in water recovery as the absorption time was extended. During the initial 6-hour absorption tests, the

system was able to recover between 195 and 225 milliliters of water when operating at an ambient relative humidity (RH) ranging from 32 to 33%, as illustrated in Figure 2.

This baseline performance established a reference point for assessing the influence of longer absorption periods. When the absorption time was increased to 8 hours, there was a notable improvement in water yield, with the device producing between 378 and 430 milliliters of water at a slightly higher

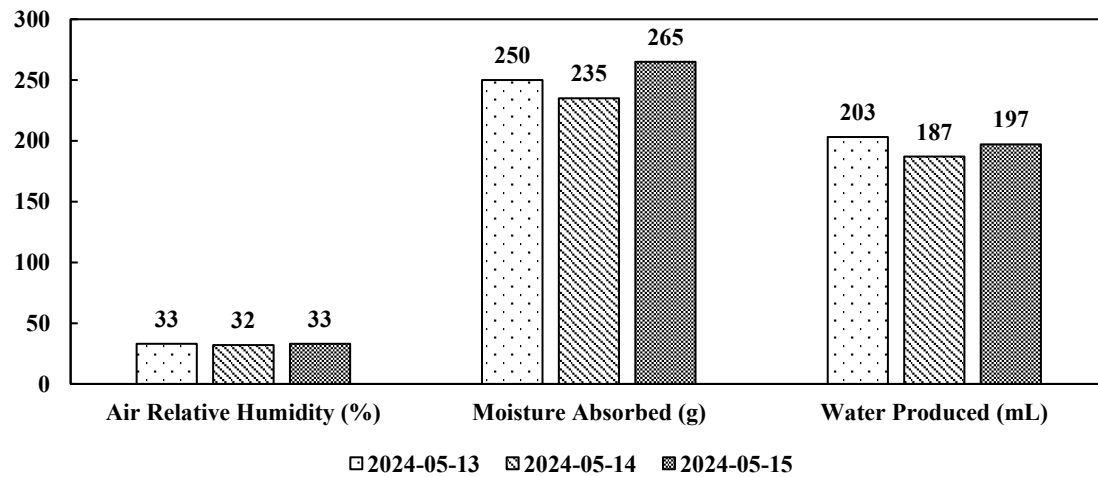


Fig. 2. Performance of the hydrogel–CaCl₂ containing dual chamber device. 6 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

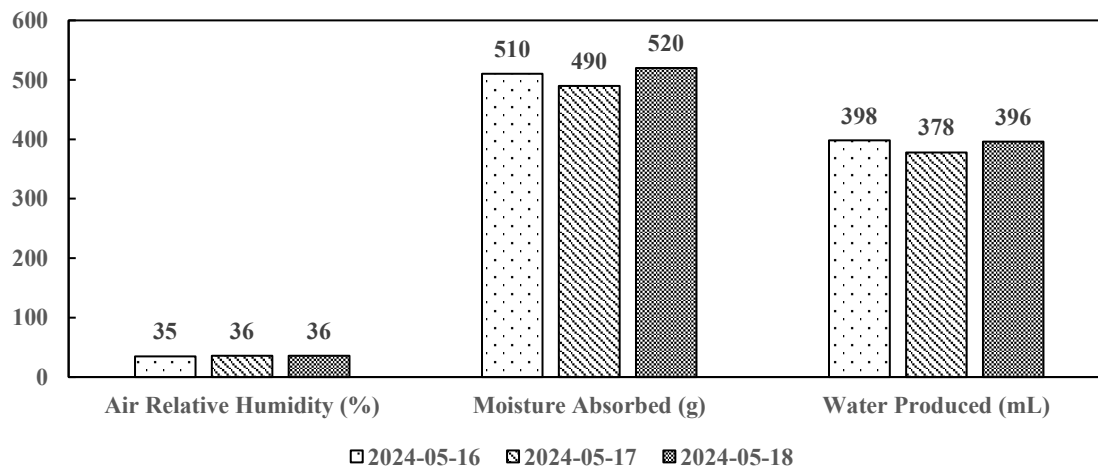


Fig. 3. Performance of the hydrogel–CaCl₂ containing dual chamber device. 8 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

ambient RH of 35 to 36%, as shown in Figure 3. This substantial increase suggests that the system continues to capture additional moisture from the air over extended periods, benefiting from the gradual saturation of the absorbent material.

Further extending the absorption duration to 12 hours resulted in an even more significant enhancement of water recovery. During these tests, the device was able to extract between 494 and 615 milliliters of water, as depicted in Figure 4. The ambient relative humidity during

this period remained consistent with earlier trials, indicating that the increased water yield is primarily attributable to the longer exposure time, which allows the hydrogel–CaCl₂ composite to absorb and retain greater amounts of atmospheric moisture.

The most remarkable performance was observed during the 24-hour absorption tests,

where the water yield increased to a range of 950 to 1055 milliliters, as seen in Figure 5. This result underscores the capacity of the system to accumulate nearly one liter of water over a full day, highlighting the effectiveness of prolonged absorption in maximizing water recovery from low-humidity environments.

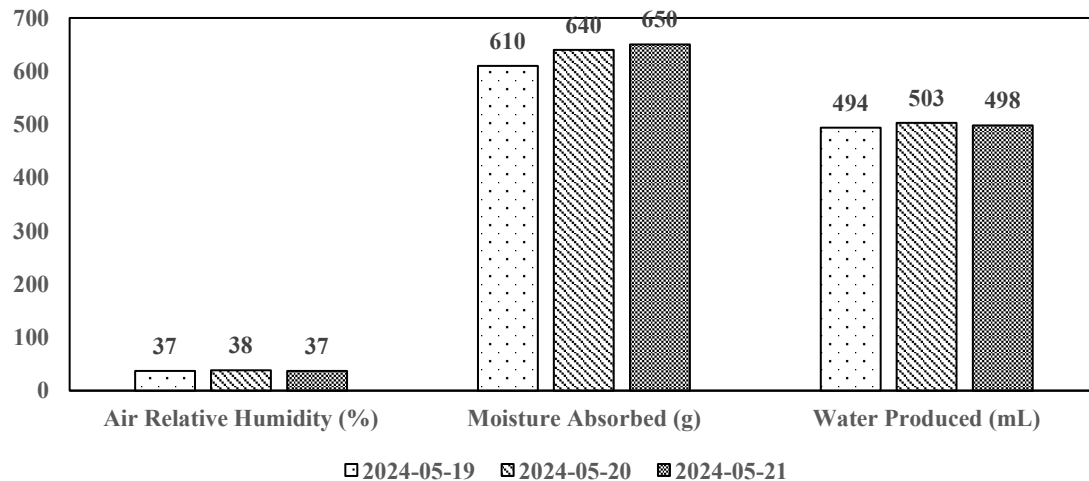


Fig. 4. Performance of the hydrogel–CaCl₂ containing dual chamber device. 12 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

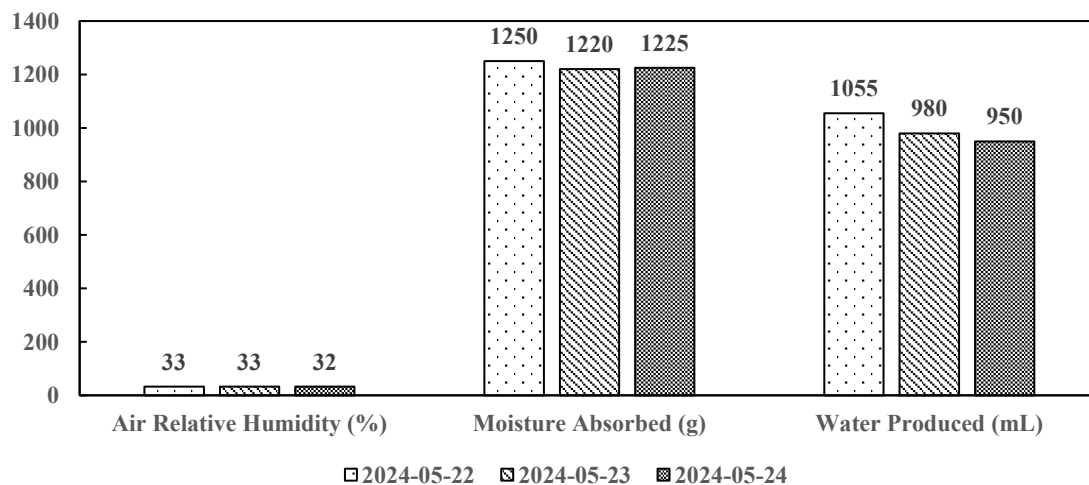


Fig. 5. Performance of the hydrogel–CaCl₂ containing dual chamber device. 24 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

Collectively, these experimental outcomes confirm two critical trends: first, the quantity of water recovered by the device consistently rises with longer absorption durations, demonstrating the time-dependent nature of moisture capture.

Second, the water yield is positively influenced by the ambient relative humidity,

with higher RH levels facilitating greater absorption.

Importantly, the hydrogel–CaCl₂ composite material used in these tests exhibited stable and repeatable performance over multiple absorption–desorption cycles. This durability indicates that the composite maintains its water capture capacity without significant

degradation or loss, making it highly suitable for practical applications.

These findings align with previous research reported by Li et al. (2018), who documented similar enhancements in water capture efficiency when using hydrogel–salt composites. Their study attributed the improved vapor sorption kinetics to the superior water transport properties enabled by the polymeric network within the hydrogel matrix, which facilitates rapid and efficient moisture uptake.

3.2. Water harvesting using pure calcium chloride

The water yields produced by the device when loaded with pure calcium chloride (CaCl₂) were significantly lower compared to those achieved using the hydrogel–CaCl₂ composite material. In the 6-hour absorption tests, the device with pure CaCl₂ was able to recover only between 83 and 86 milliliters of water, as shown in Figure 6. This initial performance was notably less than half of the water volume collected when the hydrogel composite was used under similar conditions.

Extending the absorption period to 8 hours led to a moderate increase in water recovery, with yields rising to a range of 125 to 162 milliliters, as illustrated in Figure 7. Although this represented an improvement over the shorter absorption duration, the water production remained substantially lower than the output from the hydrogel–CaCl₂

composite, highlighting the limited moisture absorption capacity of pure CaCl₂ alone.

At the 12-hour absorption period, the water yield from pure CaCl₂ continued to increase but still lagged behind the composite material. The collected water volumes ranged within similar values to the 8-hour tests, indicating a diminishing rate of improvement as time progressed Figure 8.

The highest water production achieved in the 24-hour absorption tests with pure CaCl₂ was between 187 and 198 milliliters, as depicted in Figure 9. While this amount represents the maximum water recovery for the pure salt over the full day, it is still significantly less than the nearly one liter collected when the hydrogel composite was employed for the same duration. This difference underscores the superior water absorption efficiency provided by incorporating CaCl₂ into a hydrogel matrix, which enhances moisture uptake through improved water vapor diffusion and retention properties. The relatively poor performance of pure CaCl₂ can be attributed to several inherent limitations. While CaCl₂ is highly hygroscopic and capable of absorbing moisture, in its pure salt form it tends to form a saturated brine layer on its surface as it absorbs water. This liquid layer can act as a barrier, significantly slowing down further vapor diffusion into the salt bed, thus limiting the total amount of water absorbed over time. Moreover, pure salt particles may agglomerate, reducing the effective surface area exposed to ambient air.

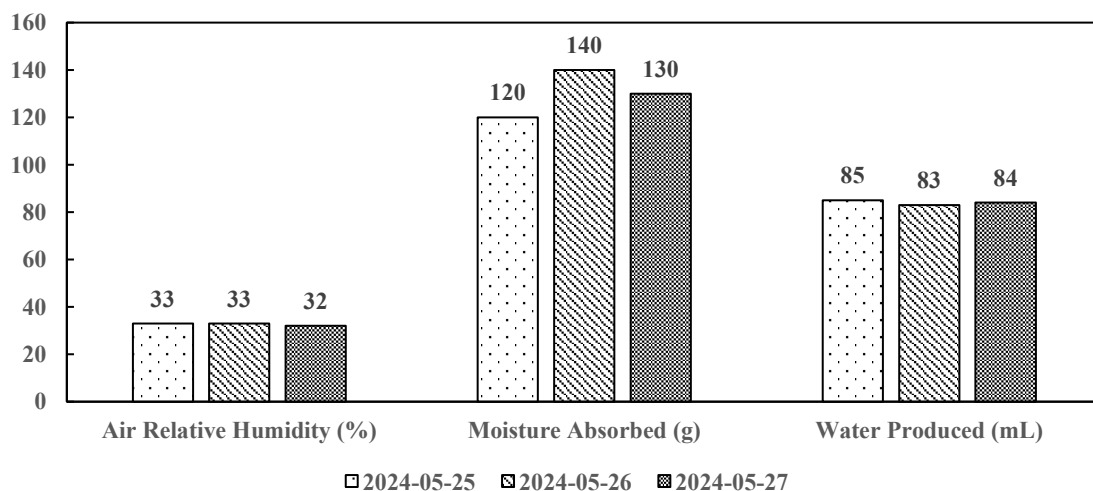


Fig. 6. Performance of the pure CaCl₂ containing dual chamber device. 6 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

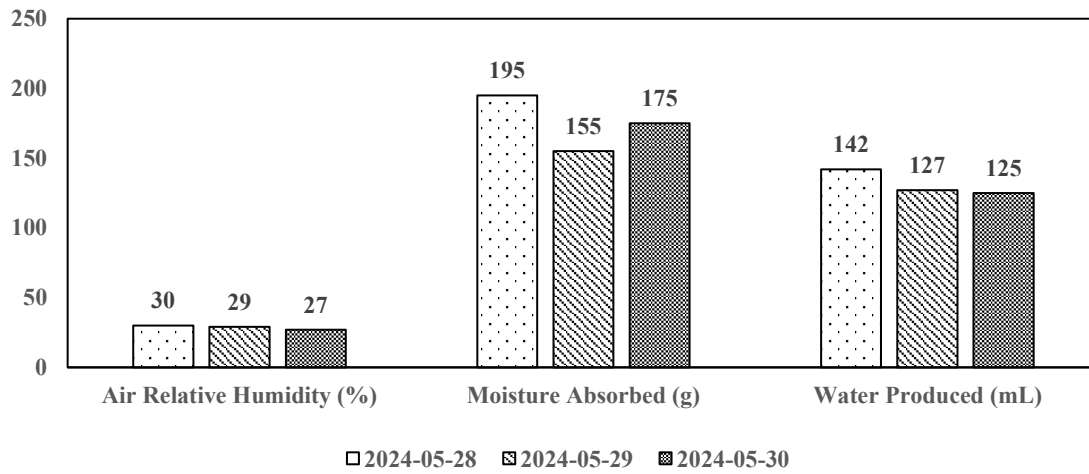


Fig. 7. Performance of the pure CaCl_2 containing dual chamber device. 8 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

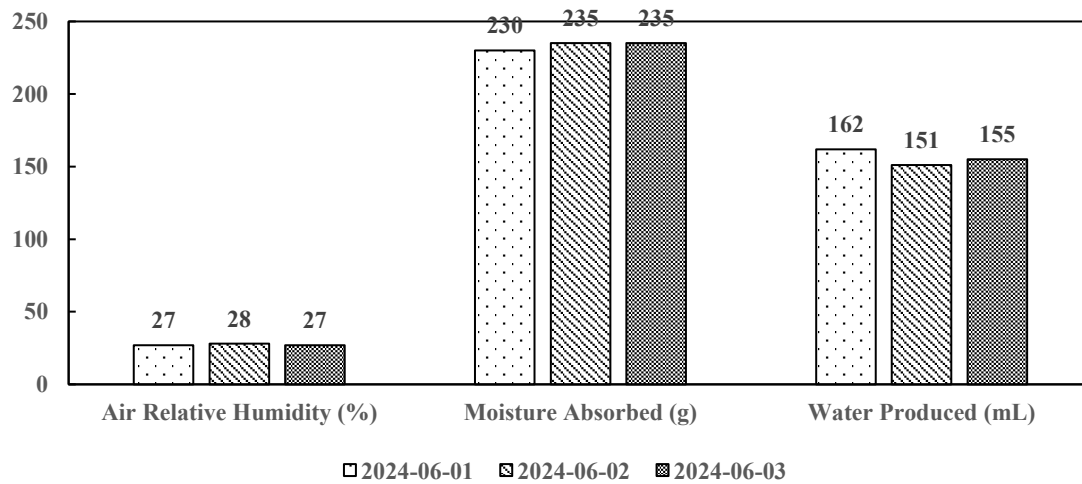


Fig. 8. Performance of the pure CaCl_2 containing dual chamber device. 12 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

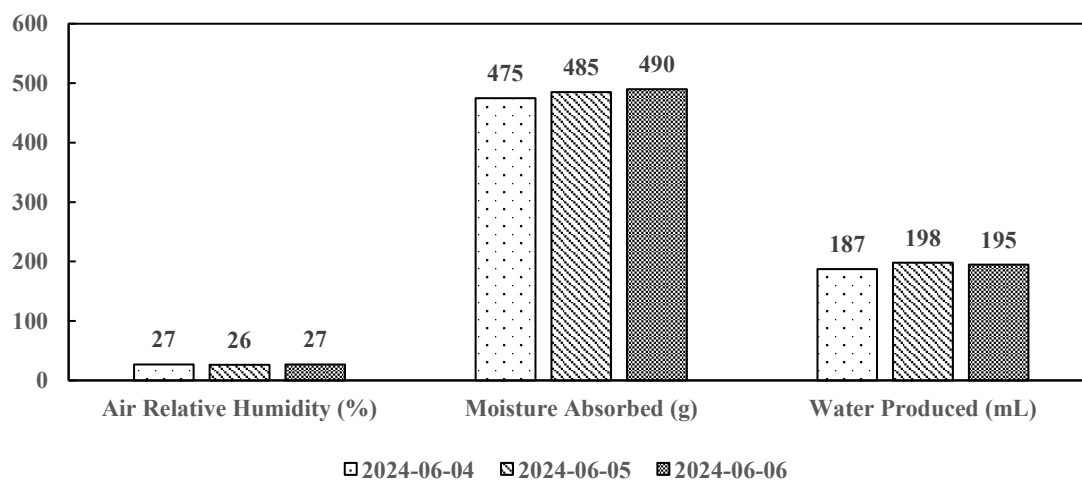


Fig. 9. Performance of the pure CaCl_2 containing dual chamber device. 24 h moisture absorption at ambient conditions in absorption chamber, followed by 4 h desorption at 100 C, and condensation of vapor in refrigeration assisted condensation chamber.

In contrast, embedding CaCl₂ within a hydrogel matrix addresses these limitations by dispersing the salt throughout a polymeric network. The hydrogel provides a porous, hydrophilic structure that facilitates rapid vapor transport to the salt particles, preventing the formation of impermeable brine layers. Additionally, the hydrogel's water-retentive properties enable it to hold larger quantities of moisture while maintaining structural integrity and surface area, which significantly improves overall absorption kinetics and capacity.

3.3. Overall performance evaluation

The results presented in Sections 4.1 and 4.2 clearly demonstrate the significant synergistic effect achieved by combining calcium chloride (CaCl₂) with a polymeric hydrogel to form a composite sorbent. This hybrid material substantially enhances both the kinetics of moisture capture from the atmosphere and the efficiency of subsequent water release during desorption, when compared to the performance of pure CaCl₂ alone.

The polymer matrix within the composite plays a critical role by improving water retention capabilities and facilitating more efficient and controlled desorption of the absorbed moisture. This behavior is consistent with previous research conducted by Ni et al. (2022) and Yang et al. (2024), who highlighted the importance of polymer-assisted sorbents in preventing salt particle agglomeration, thereby maintaining a high surface area for vapor absorption, and in improving the overall cycling stability of the sorbent over repeated absorption-desorption cycles.

Throughout all the conducted tests, the hydrogel–CaCl₂ composite consistently outperformed pure CaCl₂ in terms of both absorption capacity and water harvesting efficiency. This enhanced performance is particularly evident in the 24-hour absorption trials, where the composite achieved a water yield more than five times greater than that obtained from pure CaCl₂ under comparable environmental conditions. Such a substantial increase underscores the remarkable effectiveness of the composite material in capturing atmospheric moisture, especially over extended periods.

The electrical energy consumption of the device is an important issue that needs to be addressed carefully, if the device is going to find its way to the market. For the experiment with the largest water production (Fig.5), the two 1000 W electrical heating elements worked for 4 hours, the ¼ hp compressor worked for 6 hours, the two 16 W fans worked for 14 hours, and the 480 W power supply worked for 28 hours. So it can be calculated that 23.9 kWh electrical energy was consumed to produce around 1 L of water from ambient air moisture. Further research is needed to optimize the performance of the device to lower its electrical energy consumption.

4. Conclusion

In this study, a two-stage atmospheric water harvesting (AWH) device was successfully designed, fabricated, and tested, employing a novel hydrogel–calcium chloride (CaCl₂) composite sorbent in combination with active refrigeration for water desorption. The integration of the polymeric hydrogel matrix with CaCl₂ significantly enhanced the ability of the device to capture and release atmospheric moisture efficiently. Under ambient conditions of approximately 33% relative humidity (RH), the system demonstrated water production rates of up to 1 liter per day, representing a more than fivefold increase in yield compared to an identical device loaded with pure CaCl₂ salt.

These results clearly confirm the synergistic benefits of combining hygroscopic salts with hydrophilic polymer networks, which improve moisture sorption kinetics, prevent salt agglomeration, and enhance cycling stability over multiple absorption-desorption cycles. The polymer matrix plays a crucial role by facilitating better vapor diffusion, maintaining sorbent structural integrity, and enabling more efficient water desorption when coupled with refrigeration. This approach successfully overcomes many limitations associated with pure salt sorbents, such as brine layer formation and reduced active surface area, thereby offering a robust pathway for atmospheric water harvesting in arid and semi-arid environments.

The demonstrated performance highlights the strong potential of hydrogel–salt composites as scalable and practical materials

for atmospheric water extraction technologies. Moving forward, future research efforts should prioritize the optimization of device scale-up to increase daily water production capacity while maintaining efficiency. Additionally, energy consumption remains a critical consideration; therefore, strategies aimed at reducing the power requirements of the refrigeration stage and overall system operation are essential for real-world deployment. Integrating renewable energy sources, such as solar or wind power, could further enhance the sustainability and environmental compatibility of these devices.

Overall, this work provides evidence that polymer-assisted hygroscopic composites combined with active cooling systems represent a promising and effective approach for atmospheric water harvesting.

5. Disclosure statement

No potential conflict of interest was reported by the authors

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