# A SYSTEMATIC REVIEW OF HYBRID DEHUMIDIFICATION–WATER HARVESTING TECHNOLOGIES INTEGRATED WITH SMART BUILDINGS

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**Abstract -** Atmospheric water harvesting (AWH) is increasingly studied as a decentralized water supply option for arid and water-stressed regions, yet system performance depends strongly on ambient psychometrics and on how effectively the device perform. This review synthesizes recent progress in (i) heat-pump/direct-cooling AWH (CAWH), (ii) sorbent-based AWH (SAWH), and (iii) hybrid systems that synergically produce freshwater and dehumidify ambient air. This study compare operational configurations, performance metrics (water harvesting rate, energy consumption, and dehumidification range), optimization strategies, and water quality findings. Results show that desiccant wheel (DW) can reduce sensitivity to dry conditions by elevating dew point temperature, and enabling condensation in climates where direct cooling suffers, while advanced sorbents (hydrogels/MOF composites) promise higher uptake at lower regeneration temperatures. However, water quality can differ substantially between compressor- and desiccant-based devices and requires design-for-treatment. Key gaps include standardized metrics across device classes, configurations, multi-objective optimization that includes water quality and lifecycle energy, and validation under field conditions with dynamic weather.

**Keywords -** Desiccant Wheel, Atmospheric Water Harvesting, Smart Buildings, Hybrid HVAC Systems, Energy Management, Sustainability.

## I. INTRODUCTION

Water scarcity is intensifying globally, motivating technologies that can produce potable water with limited infrastructure [1,2]. The atmosphere constitutes a large, renewable reservoir of water vapor even in arid regions, but AWH performance is constrained by ambient humidity ratio, relative humidity, and dew point temperature (DPT) [3,4]. Traditional direct-cooling AWH condenses vapor by cooling air below its DPT; this becomes energy intensive in low humidity because substantial sensible cooling is required and frost can occur when evaporator temperatures approach or drop below 0 °C [5,6]. Desiccant-based approaches overcome some arid-climate limitations by sorbing moisture and later desorbing it into a smaller (or heated) air stream, raising water vapor partial pressure and DPT before condensation. Recent years have seen rapid advances in system integration (DW + heat pump, DW + solar heater, DW + ambient-cooled condenser), optimization methods (response surface methodology coupled with NSGA-II, mode switching based on psychometrics), hybridization for co-benefits (cooling + freshwater), and materials application (MOFs and super-hygroscopic hydrogels) [7–9].

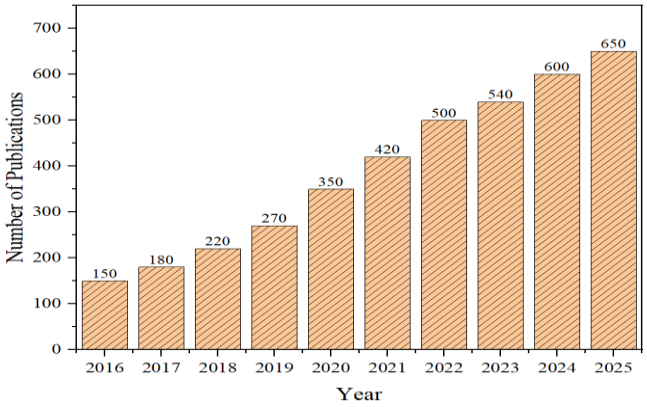



**Figure 1. The volume of scholarly publications in the field of Atmospheric Water Harvesting (AWH).**

Fig. 1 presents the number of publications in the field of AWH based on Scopus and Web of Science datasets. This review draws on a focused set of recent journal articles to summarize the state of the art and highlight key trade- offs, as illustrated in Fig 2. Following an initial screening of 70 articles, 45 were selected for detailed evaluation in this study [10].

## II. CORE AWH PATHWAYS AND SYSTEM ARCHITECTURES

### 2.1 Direct cooling / compressor dehumidifiers

Direct cooling /compressor dehumidifiers produce water by drawing humid air over a cold evaporator coil, cooling it below its dew point so moisture condenses and is collected as mentioned in Fig. 2a. A vapor‑ compression refrigeration cycle (compressor, condenser, and expansion device) continuously removes heat to maintain the coil temperature and drive condensation. Their performance strongly depends on ambient temperature and humidity, with lower dew points typically reducing water yield and increasing specific energy consumption. Field testing over >1 year in an arid US climate showed compressor units can outperform desiccant dehumidifiers when RH > 30% , T > 20 °C , and DPT > 5 °C , but become inefficient and yield-poor at lower RH and lower DPT [11]. Energy consumption varied widely (reported up to tens of kWh/L under unfavorable conditions), highlighting strong climate sensitivity and the need for operational control strategies [12].

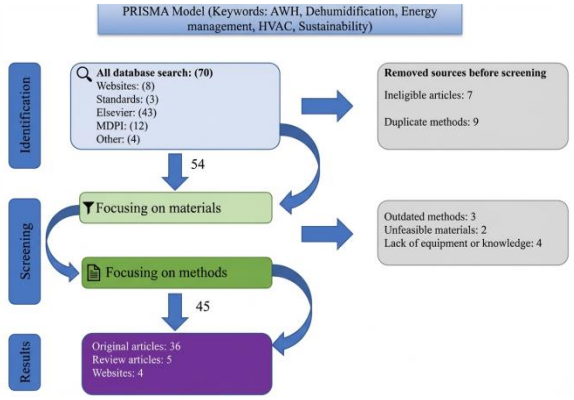



**Figure 2. Structured Pathway of Literature Screening (PRISMA).**

### 2.2 Multi-stage desiccant wheel systems

Multi-stage DW configurations can further elevate DPT and humidity ratio in the process air, boosting condensation potential as mentioned in Fig. 2b. A solar-powered AWH using two-stage DW and ambient air-cooled condenser demonstrated strong potential in cool & dry and hot & humid climates but struggled in hot & dry climates where process-air DPT remained below ambient dry-bulb, preventing ambient-cooled condensation without additional refrigeration [13]. This illustrates a central feasibility boundary: condensation requires the condenser approach temperature to be below the process air DPT, which depends on both sorption performance and regeneration heat [14].

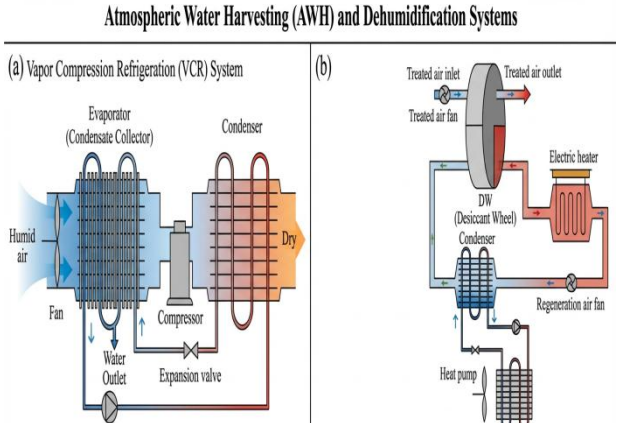



**Figure 3. (a) The HP-AWHS diagram; (b) The DW-AWHS diagram.**

### 2.3 Hybrid methods

- **cooling + water production (desiccant + evaporative cooling + HDH)**

Hybrid systems can combine building cooling and freshwater production like Fig.3. A hybrid solid desiccant M-cycle evaporative cooling system integrated with HDH desalination (SDM–HDH) compared ventilation, recirculation, and half-recirculation modes: recirculation achieved superior cooling (up to 7.91 kW) and maintained supply air below 20.85 °C and12.72 g/kg, while water production rates were similar across modes (52 kg/h order), though recirculation increased water consumption in the M-cycle (up to 5.52 kg/h) [15]. This highlights that maximizing cooling COP may increase internal water use, and net water yield must be considered [16].

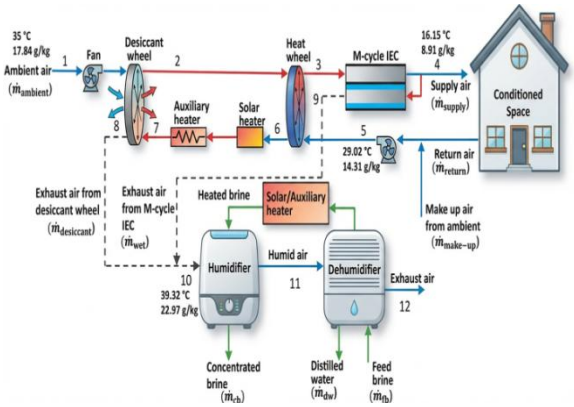



**Figure 4. Schematic diagram of SDM-HDH in ventilation mode.**

- **Desiccant-coated heat exchangers (DCHE) for multi-cyclic sorption**

In Fig.4, DCHEs apply a thin desiccant layer on heat exchanger fins to accelerate heat/mass transfer and enable multi-cyclic operation. A 1-D transient model for a plate-fin DCHE adapted to AWG found that adsorption/desorption cycle times and air velocities should be optimized independently; “secondary channel cooling” during adsorption offered limited benefit when the primary air stream already removed

adsorption heat effectively [17]. Reported best-case outcomes included specific water (SWP) up to 5.8 L $kg^{-1}$ $day^{-1}$ and specific energy consumption (SEC) as low as 7.7 MJ $L^{-1}$ under favorable conditions, but performance degraded at higher ambient temperatures due to higher saturation humidity (harder to condense water using ambient cooling) [18].

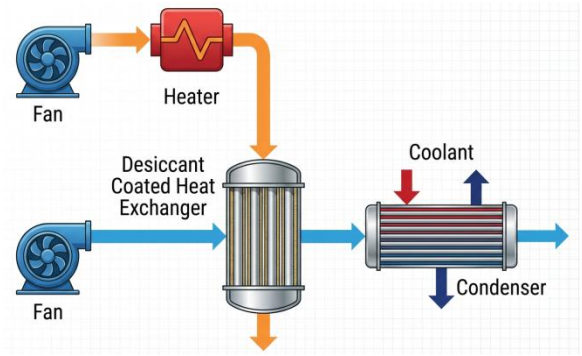



**Figure 5. Process flow diagram for the mechanism considering air configurations.**

## III. COMPARATIVE REVIEW OF METHODS AND RESULTS

### 3.1 Climate sensitivity and feasibility boundaries

Direct cooling is favored in warm-humid climates due to high DPT; DW assistance becomes advantageous as RH/DPT drop. In a global-conditions optimization, a heat-pump AWH system operating in either direct cooling mode (DCM) or DW-assisted cooling mode (DW-CM) exhibited a critical RH and humidity ratio boundary: when ambient RH and humidity ratio are above critical values, DCM minimizes daily energy; otherwise DW-CM is preferred [19]. Fig. 5 demonstrates the energy consumption for CAWH, and SAWH based on datasets of 110 industrial companies in the field of AWH [20].

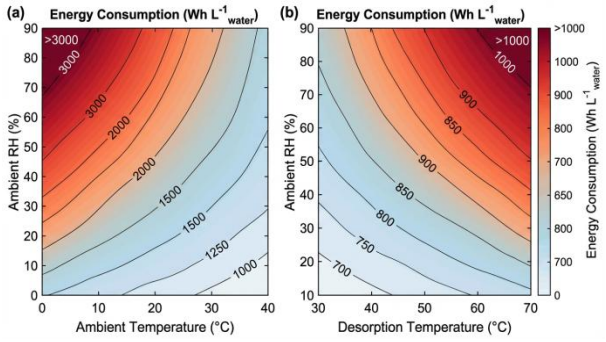



**Figure 6. Energy consumption of the water yield for different configurations. a) CAWH, B) SAWH.**

### 3.2 DW-AWHS parameter sensitivity and multi-objective optimization

DW-AWHS introduces coupled controls such as heater power increases desorption and humidification but can make condensation harder if it raises outlet temperatures or increases energy use; lower condenser temperatures improve condensation but can impair regeneration if the heat pump cycle is constrained. A combined RSM + NSGA-II framework was used to resolve the WHR–$\Delta T_{DP}$ trade-off and derive Pareto-optimal condition. The sensitivity ranking of the evaluated parameters is presented in Table 1 [21].

| Ranking | WHR | $\Delta T_{DP}$ |
|---|---|---|
| **1** | heater power | condensation temperature |
| **2** | condensation temperature | heater power |
| **3** | regeneration fan speed | regeneration fan speed |
| **4** | treated fan speed | treated fan speed |

**Table I. The ranking of effective parameters after sensitivity analysis.**

### 3.3 Water quality and yield: desiccant vs compressor collection

Water quality is a critical but sometimes overlooked dimension. In long-duration outdoor testing, compressor-collected waters showed higher conductivity (up to 180 µS/cm) , turbidity (up to 190 NTU) , and elevated metals (Al/Fe/Mn near or above secondary standards) relative to desiccant systems; DOC ranged up to 12 mg-C/L and included aldehydes and carboxylic acids [11]. Desiccant-collected water had lower turbidity and metals, with DOC always <6 mg/L; microbial counts still required disinfection. As a result, AWH needs integrated air filtration and water post-treatment; condensation method and contact with aerosols strongly shape contaminant uptake. Based on several method, different yield obtained as depicted in Fig. 6 [22–27].

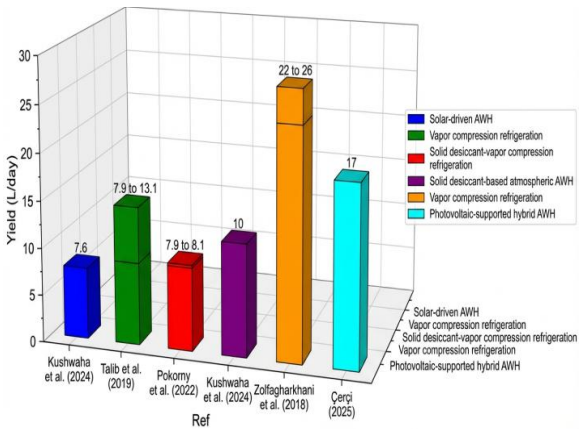



**Figure 7. Comparison of water yield based on different configurations.**

### 3.4 Advanced sorbents and low-temperature regeneration

A hydrogel composite desiccant wheel (PAM-LiCl) built on honeycomb glass fiber paper demonstrated substantially higher moisture removal than MOF composite (AlFum-LiCl) and silica gel wheels, especially at low moisture content. At 15 °C, 30% RH, moisture-content difference was 2.96 g/kg vs

1.56 g/kg (MOF) and 0.57 g/kg (silica) [28]. Performance remained strong at 30 °C, 90% RH (Δd 5.45 g/kg). Regeneration temperatures as low as 55–65 °C were effective; rotational speed had relatively minor influence within tested ranges. In conclusion as mentioned in Fig.7, sorbent innovation (hydrogels/salt composites) can shift the operating envelope toward lower-grade heat, supporting solar/waste-heat regeneration and potentially improving arid performance [29].

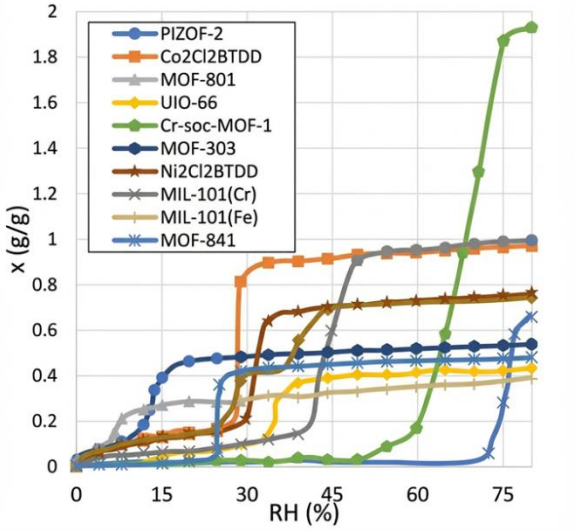



**Figure 8. Dehumidification capacity of different materials.**

### 3.5 Building HVAC integration: solar-driven DW air conditioning

Solar‑driven DW air conditioning offers a sustainable pathway for integrating HVAC systems in smart buildings like Fig. 8. By harnessing solar thermal energy to regenerate the desiccant material, these systems efficiently dehumidify and cool indoor air while reducing reliance on conventional electricity‑driven chillers [30]. This integration not only enhances energy efficiency but also supports resilient, low‑carbon building operations aligned with modern sustainability goals. A TRNSYS model for Guangzhou found optimal pump/airflow matching and reported an average electrical COP 3.8, about 1.37× that of conventional systems, with 24.7% energy saving and reduced CO2 emissions [31]. In sum, DW regeneration infrastructure (solar thermal loops, storage tanks, controls) is mature in HVAC and can be leveraged for AWH regeneration subsystems.

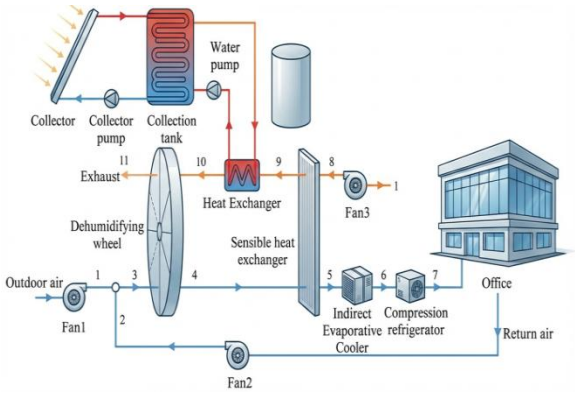



**Figure 9. Schematic of integration of dehumidification system and building**.

## IV. APPLICATIONS AND DEPLOYMENT SCENARIOS

### 4.1 Arid and semi-arid regions (low RH, low DPT)

In Fig.9, Preferred approaches are DW-assisted cooling (mode switching) with high-performance sorbents (hydrogels/MOF composites), and designs that elevate DPT before condensation are among the best scenarios, however, ambient-cooled condensers may fail when DPT remains below DBT; active cooling may still be needed in hot-dry [32].

### 4.2 Humid coastal climates (high RH, high DPT)

The direct cooling may be most energy-effective and have highest water yield in humid climate. On the other hand, DW can still help but may reduce efficiency due to added regeneration energy [33].

### 4.3 Off-grid/renewable-driven systems

Solar thermal regeneration with evacuated tube collectors enabling >100 °C air streams can support multi-stage DW systems. For Low-grade heat utilization: hydrogel wheels and low-temp sorbents can reduce required regeneration temperature to 55–75 °C, enabling more consistent solar/waste-heat use [34].

### 4.4 Co-production systems for buildings and remote communities

Integration of cooling and water desalination units like SDM–HDH style systems can co-produce cooling load and freshwater, useful where both are scarce; mode selection can optimize comfort against net water yield [35].

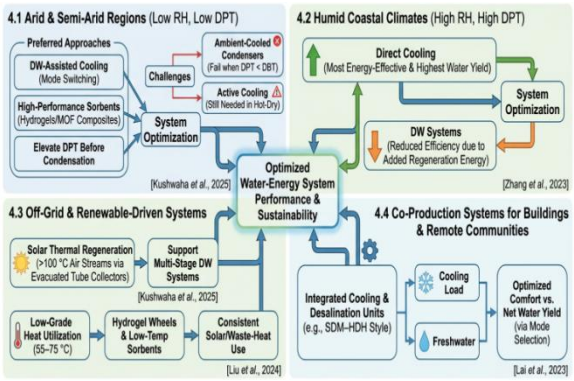



**Figure 10. Optimum applications of AWH.**

## V. RESULTS

### 5.1. Comparison

Table 2 highlights the main ideas, strengths, limitations, and results of several key studies in the field, providing a structured comparison that allows readers to quickly grasp the contributions and shortcomings of each work. By presenting these elements side by side, the table facilitates a clearer understanding of how different approaches have advanced the state of knowledge, while also identifying gaps that remain to be addressed. This synthesis serves as a foundation for evaluating current progress and guiding future research directions.

| Class | Strengths | Limitations | Typical reported outcomes |
|---|---|---|---|
| direct cooling [11] | High yield in humid/warm; commercial maturity | Strong climate sensitivity; frost risk; water quality issues from aerosols/coil contact | Yield up to 1.1 L/h; energy median 2 kWh/L but can be far higher; turbidity/metals elevated. |
| heat-pump AWH [21] | Better in dry conditions; mode switching can minimize energy | Added regeneration energy; multi-objective trade-offs; control complexity | WHR 0.216 kg/h at 20°C/40%RH with ΔT_DP 23.7°C; Zhang: WHE1–3.7 kg/kWh depending on city. |
| Solar DW [22] | High yield; low electricity for cooling | May fail in hot-dry without VCR; needs high regeneration temps/collector area | Simulated up to 6.6 L/h; experimental 14 L/day; energy eff. 9.5%. |
| DCHE [18] | High transfer rates; design/operation insights | Model assumes ideal condenser; performance drops at high ambient T | SWP up to 5.8 L/kg/day; SEC down to 7.7 MJ/L. |
| Cooling + HDH [35] | Co-produce cooling & water; uses waste air streams | Water consumption in evaporative stage; COP modest | Cooling up to7.9 kW; water production 52 kg/h. |

**Table II. Systematic synthesis the field of AWH.**

### 5.2. Research Gaps and Future Directions

Several gaps and future research directions have been identified in this field; however, the most critical aspects are outlined below.

- Standardize metrics and boundaries: WHR/WHE should be reported with explicit inclusion/exclusion of heater, fans, heat pump, and condenser assumptions; psychrometric state points should be fully defined.
- Water quality as an optimization objective: Combine performance optimization (WHR, WHE) with quality proxies (turbidity risk, VOC uptake, metals) using multi-objective frameworks similar to RSM+NSGA-II.
- Condenser realism in models: DCHE and some DW studies assume ideal condensation at ambient temperature. Real condensers impose finite UA, fouling, and aerosol carryover; coupled condenser models are needed.
- Dynamic control and mode switching in the field: Psychrometric-map mode switching is promising; and field controllers should incorporate forecasted weather, power availability, and water demand.
- Materials-to-device scale-up: Hydrogel wheel results are encouraging but need durability, salt management, long-term cycling, and integration into AWH-specific architectures.

### 5.3. Conclusions

SAWH or CAWH technologies are progressing from conceptual designs toward optimized, climate- adaptive systems. However, several critical considerations must be addressed to fully understand their potential and limitations. The following notes outline key aspects that influence performance,

scalability, and integration within sustainable building applications.

- Direct cooling is effective in humid/warm climates but can be energy-inefficient and yield-limited in dry conditions; water quality issues are nontrivial.
- DW-assisted AWH improves robustness in low humidity by elevating DPT, with optimization frameworks (RSM+NSGA-II) providing validated parameter sets and sensitivity rankings.
- Solar-driven multi-stage DW systems can achieve high yields in cool-dry and hot-humid climates using ambient cooling, but hot-dry climates may require active cooling.
- DCHE multi-cyclic reactors offer a promising path to higher sorbent utilization through enhanced transfer and cycle optimization, though condenser realism and field validation remain open.
- Advanced sorbents such as hydrogel composites can significantly reduce regeneration temperature requirements while improving moisture removal, potentially enabling broader use of low-grade heat.

Overall, the next stage of the field should integrate performance–energy–water-comfort co-optimization, validate under realistic operating constraints, and scale materials innovations into robust, maintainable AWH devices.

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