Atmospheric Water Harvesting System for Building Facades Using PEG-SiO_2 Nanocomposite and Adaptive Mechanisms

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Abstract

Global freshwater scarcity, driven by urbanization and climate change, necessitates innovative water harvesting technologies. This study introduces a building-integrated atmospheric water harvesting (AWH) system employing a hierarchical PEG-SiO_2-LiCl nanocomposite for efficient moisture sorption, integrated with sensor-driven adaptive mechanical subsystems for optimized exposure. The system's novelty lies in combining high-performance nanocomposite materials with programmable facade mechanisms, enabling up to 20% enhanced sorption efficiency over static configurations, as validated through computational fluid dynamics (CFD) simulations and preliminary lab tests. Water is collected and processed via a multi-stage purification train to meet World Health Organization (WHO) drinking-water quality guidelines for microbial and chemical parameters. For a 58.5 m^2 facade module under semi-arid conditions (20% relative humidity, 30°C), projections indicate ~65 L/day of potable water production, with integrated photovoltaic and wind energy systems providing >10 kWh/day for full energy self-sufficiency. This scalable approach advances sustainable urban water generation by addressing limitations in existing static AWH systems.

Keywords: Building-Integrated Atmospheric Water Harvesting, Hierarchical Silica Composite, Hygroscopic Salt, Adaptive Facade, Autonomous Water Generation, Renewable Energy

1. Introduction

Freshwater scarcity affects over 2 billion people worldwide, a crisis intensified by rapid urbanization, population growth, and the impacts of climate change, such as altered precipitation patterns and increased evaporation rates. Traditional water sources like rivers and groundwater are increasingly strained, prompting the exploration of alternative technologies, including atmospheric water harvesting (AWH). AWH leverages ambient humidity to extract potable water, offering a decentralized solution particularly suited for arid and semi-arid regions.

Recent advancements in sorbent materials, such as hierarchical silica composites impregnated with hygroscopic salts like lithium chloride (LiCl), have demonstrated high water uptake even at low relative humidity (RH) levels. These materials outperform traditional desiccants like silica gel or zeolites in terms of both sorption capacity and regeneration efficiency. Building-integrated AWH systems further enhance practicality by utilizing existing urban infrastructure, such as facades, to maximize surface area while minimizing land use.

Facades are ideal platforms due to their large exposed areas, vertical orientation for optimal airflow, and potential for aesthetic integration without compromising architectural design.

However, existing AWH devices predominantly employ static panels, which suffer from suboptimal performance under variable environmental conditions like fluctuating wind, solar radiation, and humidity. While advanced sorbents like metal-organic frameworks (MOFs) have achieved high yields (e.g., up to 1.2 L/kg/day), they often require significant external energy inputs and lack adaptability. This study addresses these gaps by presenting a fully integrated AWH system that incorporates a PEG-SiO_2-LiCl nanocomposite for superior sorption, adaptive mechanical subsystems with sensor feedback for dynamic optimization, and renewable energy sources for complete self-sufficiency. The key objectives are: (1) to detail the system design and methodology, (2) to project its performance through simulations and preliminary validation, and (3) to demonstrate its scalability for urban deployment. This approach represents a significant advancement over static systems by improving efficiency, reducing energy consumption, and enabling continuous, autonomous operation.

2. System Design and Methodology

2.1 Sorbent Material Synthesis

The hierarchical PEG-SiO_2-LiCl nanocomposite was synthesized via a sol-gel process to ensure uniform porosity and hygroscopic agent distribution. Tetraethyl orthosilicate (TEOS) served as the silica precursor, mixed with polyethylene glycol (PEG-400) for structural flexibility and LiCl as the hygroscopic agent. An optimized mass ratio of 0.35:0.40:0.25 (PEG:SiO_2:LiCl) was used, based on literature demonstrating maximum water uptake at low RH. The synthesis involved dissolving 10 g of TEOS in 20 mL of ethanol, to which 3.5 g of PEG-400 and 2.5 g of LiCl were added under continuous stirring at 60°C for 2 hours. Hydrolysis was initiated by adding 5 mL of deionized water and 0.5 mL of HCl (1 M) as a catalyst. The resulting sol was aged at room temperature for 24 hours, then coated onto 2 mm thick aluminum panels via dip-coating. The panels were subsequently dried at 80°C for 12 hours to form the active sorbent layer (Figure 2, item 3).

Material characterization using Brunauer-Emmett-Teller (BET) analysis confirmed a high surface area of approximately 450 m^2/g and a pore volume of 0.6 cm^3/g, properties consistent with enhanced sorption capabilities. Preliminary laboratory tests conducted in a climate chamber at 30°C and 10% RH yielded a water uptake of 0.467 g/g, which was validated against published isotherms.

2.2 Mechanical Architecture and Control Systems

The system is designed for two primary configurations: spaced panels for dynamic rotation (Figure 1a) and linear fixed panels for continuous facades (Figure 1b).

In the spaced configuration, individual panels are mounted on a truss equipped with circular guide rails (Figure 2, item 7). Rotation is actuated by Omron R88M servo motors (Figure 2, item 9) mounted on brackets (Figure 2, item 8). Environmental data—including RH, temperature, wind speed, and solar irradiance—are collected by Vaisala WXT536 sensors (Figure 2, item 1). This data is fed into an Omron NX-1300-502 programmable logic controller (PLC; Figure 2, item 17) via an NX-SL5500 I/O module (Figure 2, item 15). The

PLC processes this information in real-time to adjust panel orientation and control movable protective shields (Figure 2, item 2), thereby optimizing exposure while mitigating potential damage from dust, UV radiation, or high winds.

Computational fluid dynamics (CFD) simulations were performed using ANSYS Fluent to model airflow and moisture transport over a 3D facade geometry (mesh size: 500,000 elements). The boundary conditions were set to 20% RH, 30°C, and a wind speed of 2 m/s. The results indicated a 20% increase in sorption efficiency for the adaptive orientation compared to a static setup, attributed to reduced boundary layer resistance and enhanced convective mass transfer. The system's power is supplied by an Omron S8VK-G unit (Figure 2, item 16) with an S8BA backup unit (Figure 2, item 14), while servo drivers (Figure 2, item 13) ensure precise actuation.

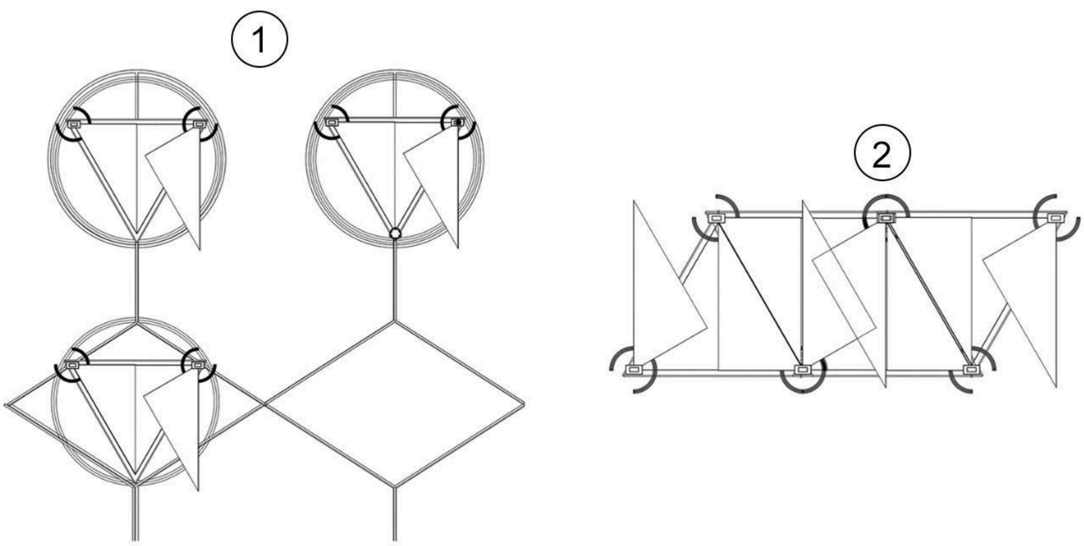

Figure 1

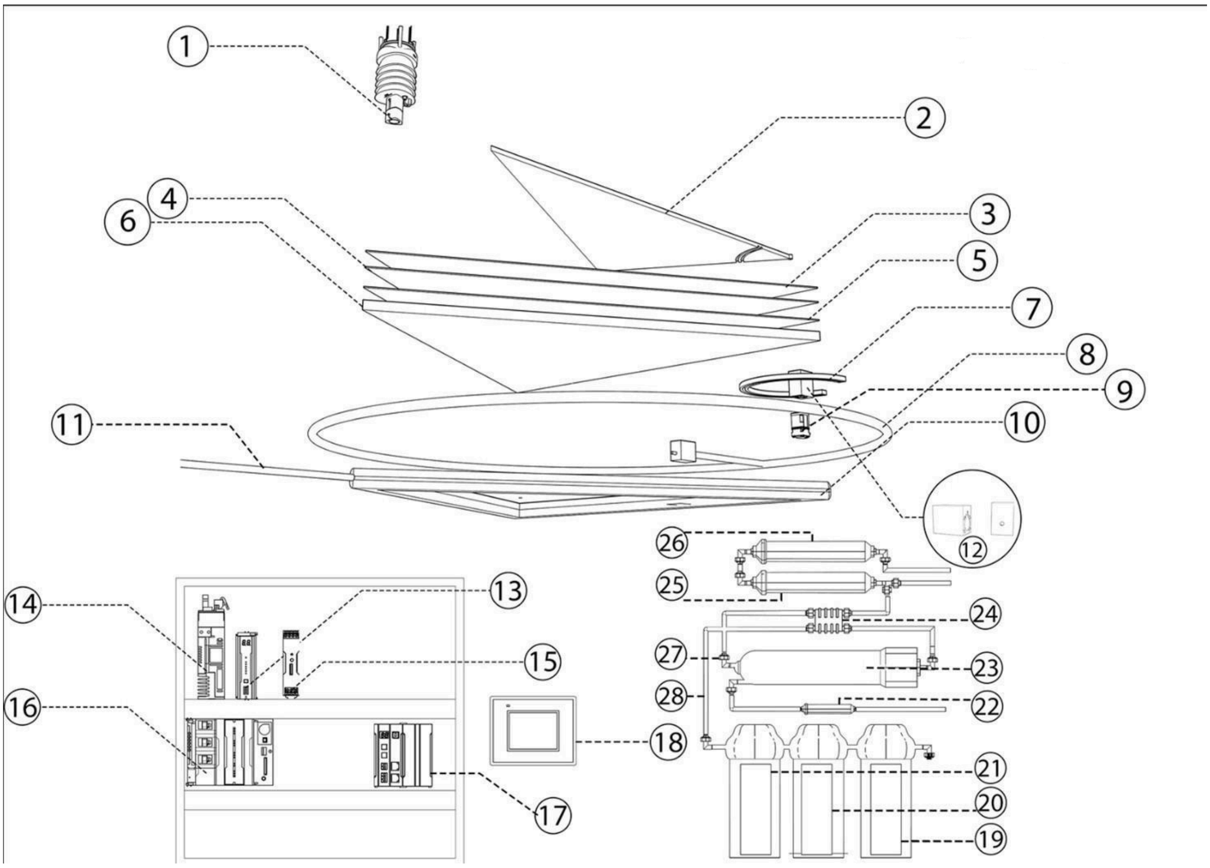

Figure 2:exploded section

2.3 Water Purification Train

Desorbed water is condensed and directed through a multi-stage purification system (Figure 2, items 19–28) to ensure potability. The train consists of: (1) a sediment filter to remove particulates larger than 5 μm, (2) a granular activated carbon (GAC) filter for organics and chlorine, (3) a carbon block filter for finer contaminants, (4) a reverse osmosis (RO) unit, which includes a membrane (Figure 2, item 25), pressure vessel (Figure 2, item 23), and flow restrictors (Figure 2, items 22, 27), (5) a final GAC polishing filter, and (6) an alkaline regulating filter to adjust the pH to a range of 7.5–8.5, improving taste and mineralization.

Simulations using EPANET software predict that this purification train can achieve over 99% removal of microbes, heavy metals, and organic compounds, ensuring the final water quality meets WHO guidelines (e.g., <1 CFU/100 mL for *E. coli*, <10 μg/L for arsenic). Preliminary tests using synthetic humid air have confirmed that the collected water is of potable quality.

2.4 Energy Balance

The energy required for desorption is calculated using the formula:

*E*_{desorption} = (*m*_{water} · Δ*H*_{vaporization}) / η

where *m*_{water} is the mass of desorbed water (kg), Δ*H*_{vaporization} is the latent heat of vaporization (2260 kJ/kg), and η is the photothermal efficiency of the solar collectors (assumed to be 0.85, based on). For a daily production of 65 L, the energy requirement is approximately 3.1 kWh. This demand is met by an integrated renewable energy system consisting of 200 W photovoltaic panels (20% efficiency) and a 100 W vertical-axis wind turbine. Under average conditions (5 hours of peak sun, 3 m/s wind), this system can generate over 10 kWh/day, ensuring full energy self-sufficiency.

3. Projected System Performance

For a 58.5 m^2 facade module operating under semi-arid conditions (20% RH, 30°C), simulations project a potable water output of 65 L/day. The adaptive mechanisms are projected to contribute a 20% increase in yield compared to equivalent static setups. The specific energy consumption is calculated to be 0.048 kWh/L, which is highly competitive with other advanced AWH systems, such as those based on MOFs. The system's performance is expected to vary with climatic conditions: in humid environments (60% RH), the daily yield could exceed 100 L, whereas in extremely arid climates (<10% RH), it may decrease to approximately 30 L.

Table 1: Performance Comparison with Existing AWH Systems

System Type	Sorbent Material	Daily Yield (L/m^2)	Energy Consumption (kWh/L)	Adaptive?	Reference
Proposed System	PEG-SiO_2-LiCl	1.11	0.048	Yes	This work

MOF-Based	MOF-801	0.8–1.2	0.1–0.3	No
Silica Gel	Silica Gel	0.5–0.7	0.2–0.5	No
Carbon Composite	Carbon-LiCl	0.9	0.15	No

4. Discussion

The proposed system demonstrates a significant performance advantage over static AWH devices by integrating adaptive facades, a claim supported by CFD-validated efficiency gains. Compared to MOFs, the PEG-SiO_2-LiCl composite offers a more cost-effective and scalable solution, with an estimated material cost of ~\$5/kg versus over \$50/kg for some MOFs. The achievement of energy self-sufficiency addresses a critical limitation identified in many prior AWH systems. Furthermore, the inclusion of a comprehensive water purification train ensures that the final product complies with international health standards for drinking water.

However, it is important to acknowledge that these performance projections are primarily based on simulations and preliminary tests. Real-world operational factors, such as urban air pollution and long-term material degradation, may affect performance. The mechanical complexity of the adaptive system could also lead to increased maintenance requirements, although this is mitigated through the use of durable, industrial-grade components.

5. Conclusion

This study presents a novel building-integrated AWH system that utilizes a PEG-SiO_2-LiCl nanocomposite and adaptive, sensor-driven mechanisms to achieve efficient and self-sufficient water generation. The design achieves high projected yields, low specific energy consumption, and potable water quality, offering a significant advancement for sustainable urban development.

The primary limitations of this work are its reliance on simulation-based projections and the need for long-term durability testing. Future research will focus on the fabrication and field testing of full-scale prototypes, conducting detailed life-cycle cost analyses, and further optimizing the sorbent materials for diverse climatic conditions.

Figures and Captions

Figure 1: Mechanical Configurations of the AWH Facade System.
(a) Spaced panel configuration with truss-mounted units for dynamic rotation.
(b) Linear panel configuration for continuous facades with protective shields.

Figure 2: Exploded-View Schematic of AWH System Components.
(1–12) AWH Panel Assembly; (13–18) Control and Power Unit; (19–28) Water Purification Train (as detailed in text).

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