# DEVELOPMENT AND EVALUATION OF SUSTAINABLE ATMOSPHERIC WATER HARVESTING SYSTEM FOR DIVERSE CLIMATIC CONDITIONS

**RAVEESH G**

**DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING**
**INDIAN INSTITUTE OF TECHNOLOGY DELHI**
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# Development and Evaluation of Sustainable Atmospheric Water Harvesting System for Diverse Climatic Conditions

***by***

RAVEESH G

Department of Energy Science and Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

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# Declaration

I hereby declare that the work presented here in the thesis entitled "**Development and Evaluation of Sustainable Atmospheric Water Harvesting System for Diverse Climatic Conditions**" has been carried out by me towards the partial fulfilment of the requirement for the award of the degree of Doctor of Philosophy at the Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The content of this thesis, in full or in parts, has not been submitted to any other Institute or University for the award of any degree or diploma by me.

Raveesh G

Entry No: 2020ESZ8170

Email: raveesh.g@ces.iitd.ac.in

Place: New Delhi

Date: 23-06-2025

# Certificate

This is to certify that the thesis entitled "**Development and Evaluation of Sustainable Atmospheric Water Harvesting System for Diverse Climatic Conditions**" being submitted by **Mr. Raveesh G** in fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work performed by him under our guidance and supervision at **Department of Energy Science and Engineering, Indian Institute of Technology Delhi.**

Further, the results obtained herein have not been submitted in part or in full to any other University or Institute for the award of any degree to the best of our knowledge.


S K Tyagi

Professor
Dept. of Energy Science and Engineering
Indian Institute of Technology Delhi

Rahul Goyal

Associate Professor
Dept. of Energy Science and Engineering
Indian Institute of Technology Delhi

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# Abstract

Water scarcity has emerged as a potentially pressing global challenge, necessitating the urgent need of novel and sustainable technologies to address this issue on priority. This research is an attempt to address the critical issue of water scarcity by advancing innovative atmospheric water harvesting (AWH) technologies, with a particular emphasis on the needs of water-stressed rural communities. The study initially explored the active refrigeration-based commercial AWH systems of residential scale with a cooling capacity of 1.5 kW and minimum water generation capacity of 20 L/day at 25ºC ambient temperature and 60% relative humidity. Their performance was evaluated through modelling in MATLAB Simscape environment, followed by experimental validation, and feasibility analysis in water-stressed cities across India. The specific energy consumption varied between 0.345 kWh/L to 0.762 kWh/L under hot and humid conditions while it varies between 1 kWh/L to 3.4 kWh/L at low dew point conditions. To improve AWH system performance and extend operation during unfavourable periods, a monthly variable airflow rate control strategy was investigated and found to be beneficial over constant airflow. The average daily productivity of the AWH system was quantified through a water generation map for all months of the year across the selected cities, allowing for the identification of favourable operational periods. While these systems demonstrated potential for scalable urban applications, their high energy consumption in low-humidity and unfavourable climatic conditions highlighted the need for more sustainable alternatives for rural areas.

To meet these challenges, a novel biomass-derived composite sorbent was synthesized using activated carbon derived from waste sugarcane bagasse impregnated with $CaCl_2$ salt. The activated carbon was synthesised using an optimized two-step chemical activation method, resulting in a high specific surface area of 2280.5 $m^2/g$ and pore volume of 1.69 $cm^3/g$, projecting it as an efficient host matrix for holding the hygroscopic salt.

Experimental investigations confirmed excellent water uptake with faster adsorption-desorption kinetics, stability over multiple cycles with good storage reliability with minimal degradation even after 10 months. The sorbent demonstrated reasonably good water uptake in a broad relative humidity band ranging from 10-90%, with a water uptake ranging from 0.24 to 2.44 g/g, showing its feasibility even at arid location. At moderate temperature and humidity (25$^{o}$C, 60% RH), the prepared sorbent exhibited a water uptake of 1.2 g/g and achieved over 80% of its equilibrium water uptake within 90 minutes. Also, the sorbent showed excellent solar driven desorption with desorption efficiencies reaching over 93% and 85% for 1 sun and 0.5 sun illumination, respectively, within 60 minutes. The practical solar-driven atmospheric water harvesting performance of the developed composite was also successfully demonstrated using a custom-built proof-of-concept device under outdoor conditions and the harvested water met the quality standards of drinking water. Furthermore, the optimum parameters for the developed sorbent were identified through simulation of vapour transport and adsorption using the COMSOL Multiphysics platform. The optimum sorbent layer porosity was found to be in the range of 0.6 to 0.7, with an optimal thickness of 4 mm, ensuring efficient and scalable AWH performance. Based on a theoretical framework, the sorption-based AWH potential was predicted to vary between 1.0 and 4.0 L/m$^2$/day under a single-cycle passive solar-assisted operation across diverse climatic conditions in India and was represented through an atmospheric water harvesting potential map.

This research provides a scalable and sustainable roadmap for AWH solutions, offering practical guidelines to address the unique challenges of both urban and rural communities. By demonstrating a sustainable, low-cost, and passive solar-compatible AWH system, this study contributes to the advancement of sustainable atmospheric water harvesting technologies for diverse climatic conditions.

# सार

जल की कमी एक संभावित गंभीर वैश्विक चुनौती के रूप में उभरी है, जिससे इस मुद्दे को प्राथमिकता के आधार पर हल करने के लिए नवीन और टिकाऊ तकनीकों की तत्काल आवश्यकता है। यह शोध जल की कमी के गंभीर मुद्दे को हल करने के लिए नवीन वायुमंडलीय जल संचयन (AWH) तकनीकों को आगे बढ़ाने का एक प्रयास है, जिसमें जल-तनावग्रस्त ग्रामीण समुदायों की आवश्यकताओं पर विशेष जोर दिया गया है। अध्ययन की शुरुआत में सक्रिय रेफ्रिजरेशन-आधारित व्यावसायिक वायुमंडलीय जल संचयन (AWH) प्रणालियों का परीक्षण किया गया, जो आवासीय स्तर की थीं और जिनकी शीतलन क्षमता 1.5 किलोवाट थी तथा 25°C परिवेश तापमान और 60% सापेक्ष आर्द्रता की स्थिति में न्यूनतम जल उत्पादन क्षमता 20 लीटर प्रति दिन थी। उनके प्रदर्शन का मूल्यांकन MATLAB सिमस्केप वातावरण में मॉडलिंग के माध्यम से किया गया, इसके बाद प्रायोगिक सत्यापन और भारत भर के जल-तनावग्रस्त शहरों में व्यवहार्यता विश्लेषण किया गया। AWH प्रणाली के प्रदर्शन को बेहतर बनाने और प्रतिकूल अवधि के दौरान संचालन का विस्तार करने के लिए, एक मासिक परिवर्तनीय वायु प्रवाह दर नियंत्रण रणनीति की जांच की गई और इसे निरंतर वायु प्रवाह की तुलना में फायदेमंद पाया गया। AWH प्रणाली की औसत दैनिक उत्पादकता को चयनित शहरों में वर्ष के सभी महीनों के लिए जल उत्पादन मानचित्र के माध्यम से निर्धारित किया गया था, जिससे अनुकूल परिचालन अवधि की पहचान की जा सके। जबकि इन प्रणालियों ने स्केलेबल शहरी अनुप्रयोगों के लिए क्षमता का प्रदर्शन किया, कम आर्द्रता और प्रतिकूल जलवायु परिस्थितियों में उनकी उच्च ऊर्जा खपत ने ग्रामीण क्षेत्रों के लिए अधिक टिकाऊ विकल्पों की आवश्यकता पर प्रकाश डाला।

इन चुनौतियों का सामना करने के लिए, $CaCl_2$ नमक के साथ गन्ने की खोई से प्राप्त सक्रिय कार्बन का उपयोग करके एक नव बायोमास-व्युत्पन्न समग्र सोरबेंट को संश्लेषित किया गया था। सक्रिय कार्बन को एक अनुकूलित दो-चरण रासायनिक सक्रियण विधि का उपयोग करके संश्लेषित किया गया था, परिणाम स्वरूप 2280.5 मीटर$^2$/ ग्राम उच्च विशिष्ट सतह क्षेत्र और 1.69 सेमी$^3$/ ग्राम का छिद्र आयतन प्राप्त हुआ,

जिससे यह आर्द्रताग्राही (हाइग्रोस्कोपिक) नमक को संचित करने के लिए एक प्रभावी मेज़बान मैट्रिक्स के रूप में उभरा। प्रायोगिक जांच ने 10 महीने के बाद भी संग्रहण क्षमता में न्यूनतम गिरावट के साथ अच्छी भंडारण विश्वसनीयता के साथ कई चक्रों पर स्थिरता, तेजी से अवशोषण-विलोपन गतिकी के साथ उत्कृष्ट जल अवशोषण की पुष्टि की। सोरबेंट ने 10-90% की सीमा में व्यापक सापेक्ष आर्द्रता बैंड में यथोचित रूप से अच्छा जल अवशोषण प्रदर्शित किया, जिसमें 0.24 से 2.44 ग्राम/ ग्राम तक जल अवशोषण था, जो शुष्क स्थान पर भी इसकी दक्षता दर्शाता है। मध्यम तापमान और आर्द्रता (25°C, 60% RH) पर, तैयार सोरबेंट ने 1.2 ग्राम/ ग्राम का जल अवशोषण प्रदर्शित किया और 90 मिनट के अंदर अपने संतुलन जल अवशोषण का 80% से अधिक प्राप्त किया। इसके अलावा, सोरबेंट ने 60 मिनट के अंदर क्रमशः 1 सूर्य और 0.5 सूर्य रोशनी के लिए 93% और 85% से अधिक तक पहुंचने वाली अवशोषण दक्षताओं के साथ उत्कृष्ट सौर संचालित विशोषण दिखाया। विकसित कंपोजिट के व्यावहारिक सौर-चालित वायुमंडलीय जल संचयन प्रदर्शन को भी बाहरी परिस्थितियों में कस्टम-निर्मित प्रूफ-ऑफ-कॉन्सेप्ट डिवाइस का उपयोग करके सफलतापूर्वक प्रदर्शित किया गया और और प्राप्त जल पीने योग्य जल गुणवत्ता मानकों पर खरा उतरा। इसके अलावा, विकसित सॉर्बेंट के लिए इष्टतम मापदंडों की पहचान COMSOL मल्टीफिजिक्स प्लेटफॉर्म का उपयोग करके वाष्प परिवहन और अवशोषण के सिमुलेशन के माध्यम से की गई थी। इष्टतम सॉर्बेंट परत छिद्रण 0.6 से 0.7 की सीमा में पाया गया, जिसमें 4 मिमी की इष्टतम मोटाई थी, जो कुशल और स्केलेबल AWH प्रदर्शन सुनिश्चित करता है। एक सैद्धांतिक ढांचे के आधार पर, भारत में विविध जलवायु परिस्थितियों में एकल-चक्र निष्क्रिय सौर-सहायता वाले संचालन के तहत सोखना-आधारित AWH क्षमता 1.0 और 4.9 $L/m^2$/दिन बीच अनुमानित की गई, जिसे एक वायुमंडलीय जल संचयन संभाव्यता मानचित्र के रूप में प्रस्तुत किया गया।

यह शोध वायुमंडलीय जल संचयन (AWH) के लिए एक स्केलेबल और टिकाऊ रोडमैप प्रदान करता है, जो शहरी और ग्रामीण दोनों समुदायों की विशिष्ट चुनौतियों को संबोधित करने के लिए व्यावहारिक दिशानिर्देश प्रस्तुत करता है। एक सतत, कम लागत वाले और सौर-संगत निष्क्रिय AWH प्रणाली का

प्रदर्शन कर यह अध्ययन विविध जलवायु परिस्थितियों के लिए टिकाऊ वायुमंडलीय जल संचयन तकनीकों की प्रगति में योगदान देता है।

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# Nomenclature

**Symbols**

| | |
|---|---|
| $A_t$ | Total surface area of heat exchanger ($m^2$) |
| $A_{unfin}$ | Unfinned area ($m^2$) |
| $A_{fin}$ | Total surface area of fins ($m^2$) |
| $A_c$ | Cross-sectional area of fin ($m^2$) |
| C | Constant, defined in eq. (3.4) |
| $C_s$ | Vapour concentration in the salt crystals ($mol/m^3$) |
| $C_p$ | Vapour concentration in the pores ($mol/m^3$) |
| $C_{pm}$ | Specific heat capacity of moist air (kJ/kg K) |
| $C_a$ | Specific heat capacity of dry air (kJ/ kg K) |
| $C_{ma}$ | Specific heat capacity of the air at saturated conditions (kJ/ kg K) |
| $C_{min}$ | Minimum heat capacity rate (W/ K) |
| D | Outside diameter of tube (m) |
| $D_v$ | Intercrystalline diffusivity ($m^2/s$) |
| $D_{v,a}$ | Molecular diffusivity of water vapour in air ($m^2/s$) |
| $D_p$ | Diagonal tube spacing (m) |
| $f_t$ | Friction factor |
| $Hg$ | Hagen number |
| $H_p$ | Horizontal pitch (m) |
| $h_{a, in}$ | Specific enthalpy of inlet air (kJ/kg) |
| $h_{a, out}$ | Specific enthalpy of outlet air (kJ/kg) |
| $h_{a, adp}$ | Specific enthalpy of saturated air at apparatus dew point temperature (kJ/kg) |
| $h_a$ | Air side convective heat transfer coefficient ($W/m^2$ K) |
| $h_m$ | Convective mass transfer coefficient (kg/s $m^2$) |
| $h_r$ | Refrigerant side convective heat transfer coefficient ($W/m^2$ K) |
| $h_{fg}$ | Latent heat of condensation (kJ/kg) |
| k | Sorption rate constant ($s^{-1}$) |
| $k_t$ | Thermal conductivity (W/m K) |
| $L_1$, $L_2$ | Parameters to estimate hypothetical fin length (m) |
| $Le$ | Lewis number |
| $Lq$ | Lévêque number |

| | |
|---|---|
| $m_t$ | Instantaneous mass of the sorbent during sorption (g) |
| $m_d$ | Initial dry mass of the sorbent (g) |
| $M_w$ | Wet fin parameter, defined in eq. (3.6) |
| $M_{water}$ | Molar mass of water (g/mol) |
| $\dot{m}_w$ | Water generation rate (kg/s) |
| $\dot{m}_a$ | Mass flow rate of moist air (kg/s) |
| $m_e$ | Mass of the sorbent after saturation (g) |
| Nu | Nusselt number |
| P | Perimeter (m) |
| $P_{sat}$ | Saturated vapour pressure (Pa) |
| Pr | Prandtl number |
| $P_s$ | Pressure of moist air at saturation condition (Pa) |
| Q | Rate of heat transfer between refrigerant and moist air (W) |
| $Q_{zone}$ | Rate of heat transfer occurring in a particular zone or phase (W) |
| R | Gas constant (J/kg K) |
| Re | Reynolds Number |
| $R_{eq}$ | Equivalent fin radius (m) |
| $R_{total}$ | Total thermal resistance (K/W) |
| $R_w$ | Wall thermal resistance (K/W) |
| r | Tube radius (m) |
| t | Time (seconds) |
| T | Ambient air temperature |
| $T_f$ | Fin element temperature (°C) |
| $T_{a, in}$ | Temperature of the inlet air (°C) |
| $T_{a, out}$ | Temperature of the outlet air (°C) |
| $T_{aw, in}$ | Wet bulb temperature of the inlet air (°C) |
| $T_{min}$ | Cooling coil temperature (°C) |
| $T_{r, in}$ | Temperature of the refrigerant at the inlet of evaporator (°C) |
| $T_{wall}$ | Approximate cooling coil surface temperature (°C) |
| $V_p$ | Vertical pitch (m) |
| w | Water uptake, mass of water adsorbed per unit dry mass of sorbent (g/g) |
| $w_e$ | Equilibrium water uptake (g/g) |
| $x$ | Distance measured from fin base to the fin element (m) |
| $X_i, X_o$ | Refrigerant vapour quality at the inlet and outlet of the phase change section |

| | |
|---|---|
| z | Zone length fraction |

**Greek Symbols**

| | |
|---|---|
| ε | Sorption potential (kJ/kg) |
| ∈ | Porosity |
| $\varepsilon_e$ | Evaporator coil effectiveness |
| $\in_{HX}$ | Heat exchanger effectiveness |
| $\eta_f$ | Dry fin efficiency |
| $\eta_{wet\ fin}$ | Wet fin efficiency |
| $\rho_{bed}$ | Sorbent bed density ($kg/m^3$) |
| $\rho_s$ | Absolute density of the sorbent particles ($kg/m^3$) |
| $\rho_{sl}$, $\rho_{sv}$ | Refrigerant density at saturated liquid and saturated vapour states ($kg/m^3$) |
| $\phi$ | Fin parameter, defined in eq. (8) |
| ω | Humidity ratio of saturated air at fin element temperature (kg/kg) |
| $\omega_{a,\ in}$ | Humidity ratio of the inlet air (kg/kg) |
| $\omega_{a,\ out}$ | Humidity ratio of the outlet air (kg/kg) |
| $\omega_{a,\ adp}$ | Humidity ratio of the saturated air at apparatus dew point temperature (kg/kg) |
| $\omega_{min}$ | Minimum humidity ratio (kg/kg) |
| $\omega_{wall}$ | Humidity ratio of air close to heat transfer surface temperature (kg/kg) |

**Abbreviations**

| | |
|---|---|
| AWH | Atmospheric Water Harvesting |
| COP | Coefficient of Performance |
| LDF | Linear Driving Force |
| MHI | Moisture Harvesting Index |
| NTU | Number of Transfer Units |
| RH | Relative Humidity (%) |
| SEC | Specific Energy Consumption (kWh/L) |
| SBAC | Sugarcane bagasse derived activated carbon |
| TR | Ton of refrigeration |
| VCR | Vapour Compression Refrigeration |
| WGR | Water Generation Rate (L/h) |