Development and Evaluation of Sustainable Atmospheric Water Harvesting System for Diverse Climatic Conditions

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 25°C 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°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 4.9 $L/m^2/day$ 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.