International Journal of Scientific Research in Mechanical and Materials Engineering
Available online at : www.ijsrmme.com
ISSN : 2457-0435 doi : https://doi.org/10.32628/IJSRMME

Sustainable Development of an Evaporative Cooling System for Rural and Off-Grid Applications

Yash R Watpade*[1], Sanskar D Mapari[1], Harshvardhan A Kale[1], Mayur M Ingale[1], Shoeb A Khan[2]
*[1]Third Year Diploma Students of Mechanical Engineering, MET's Institute of Technology-Polytechnic, Nashik, Maharashtra, India
[2]Lecturer in Mechanical Engineering, MET's Institute of Technology-Polytechnic, Nashik, Maharashtra, India

ARTICLEINFO

Article History:
Accepted : 05 March 2026
Published : 25 March 2026

Publication Issue
Volume 10, Issue 2
March-April-2026

Page Number
40-46

ABSTRACT

The increasing demand for cooling and concerns about energy consumption and air pollution have created a need for sustainable cooling solutions. Conventional air-conditioning systems consume large amounts of electricity and use refrigerants that contribute to global warming. This project presents a sustainable evaporative cooling system using honeycomb cellulose pads and terracotta tubes. The system operates on evaporative cooling, where water evaporation lowers the air temperature and helps capture particulate matter. The system achieves 6–10 °C temperature reduction, improves air quality, and saves 75–80% energy compared to conventional cooling systems. It is a low-cost, eco-friendly, and energy-efficient solution suitable for hot and dry regions.

Keywords: Evaporative Cooling System, Sustainable, Natural Cooling System

1. Introduction

The increasing demand for thermal comfort in industrial, commercial, and residential sectors has led to a rapid rise in global energy consumption. Conventional vapor-compression air-conditioning systems dominate the cooling market due to their ability to provide precise temperature control; however, they are highly energy-intensive and rely on synthetic refrigerants that contribute significantly to global warming and ozone depletion. Cooling systems alone account for a substantial share of total electricity consumption, especially in hot climatic regions, thereby increasing operational costs and environmental burden.

In parallel with energy concerns, air pollution has emerged as a critical global challenge. Particulate matter, is recognized as one of the most harmful air pollutants due to its ability to penetrate deep into the respiratory system and bloodstream. Major sources of particulate emissions include industrial exhausts, diesel generator sets, vehicular emissions, and HVAC condenser discharge air. Prolonged exposure to fine particulate matter has been linked to respiratory illnesses, cardiovascular diseases, and reduced life expectancy. Therefore, technologies that can

Copyright © 2026 The Author(s): This is an open-access article distributed under the terms of the Creative Commons Attribution **4.0 International License (CC BY-NC 4.0)**

simultaneously address cooling requirements and particulate matter mitigation are of increasing importance.

Evaporative cooling has gained renewed attention as a sustainable alternative to conventional air-conditioning systems, especially in hot and dry climates. The working principle of evaporative cooling is based on the adiabatic evaporation of water, where sensible heat from the air is converted into latent heat, resulting in a reduction in air temperature. Compared to vapor-compression systems, evaporative coolers offer advantages such as low energy consumption, simple construction, and minimal environmental impact due to the absence of refrigerants. Direct evaporative cooling systems, in particular, are widely studied for their cost-effectiveness and suitability for large-scale air handling applications.

Recent research has shown that wetted media used in evaporative cooling systems can also act as effective collectors of airborne particulate matter. Water films formed on porous surfaces capture dust and fine particles through inertial impaction, interception, and diffusion mechanisms. Materials such as cellulose pads, ceramic elements, and terracotta structures have demonstrated enhanced evaporation rates due to their high surface area and capillary properties, while simultaneously improving particulate removal efficiency. This dual functionality makes evaporative cooling systems promising candidates for integrated thermal management and air quality control.

Despite these advantages, the performance of evaporative cooling systems is strongly influenced by the choice of cooling media, system configuration, and operating conditions. There remains a need for low-cost, locally available, and sustainable materials that can enhance both cooling effectiveness and particulate matter reduction without increasing energy consumption. In this context, the present work focuses on the development and experimental evaluation of a sustainable direct evaporative cooling system employing honeycomb cellulose cooling pads in combination with porous pottery (terracotta) tubes. The objective is to investigate its cooling performance, energy efficiency, and particulate matter mitigation potential, thereby providing an environmentally friendly solution for industrial exhaust cooling, agricultural applications, and sustainable building systems.

1.1 Research Gap

Existing studies on evaporative cooling systems mainly focus on thermal performance, energy efficiency, and climatic suitability, with limited emphasis on air quality improvement. Similarly, research on air pollution primarily addresses health impacts and standalone water-based particulate matter suppression techniques, without integrating cooling performance or energy analysis. Recent works on terracotta- and ceramic-based evaporative cooling systems demonstrate enhanced evaporation and temperature reduction; however, their capability for particulate matter mitigation is rarely quantified or experimentally validated. Moreover, integrated systems that simultaneously evaluate cooling effectiveness, energy savings, and particulate matter reduction using low-cost, sustainable materials remain limited. Hence, there is a lack of comprehensive experimental studies addressing the dual functionality of evaporative cooling systems for both thermal management and particulate matter control.

1.2 Scope of work

The scope of the present project involves the design, development, and experimental evaluation of a sustainable direct evaporative cooling system aimed at providing energy-efficient cooling while improving air quality. The proposed system utilizes honeycomb cellulose cooling pads in combination with porous pottery (terracotta) tubes to enhance the evaporative cooling process and enable the reduction of particulate matter from the air stream. The study focuses on understanding the thermal behavior of the system, its particulate matter mitigation capability, and its overall energy performance under controlled

operating conditions. The system is intended for applications in hot and dry climatic regions, where conventional cooling systems consume significant energy and contribute to environmental degradation. The project also emphasizes the use of low-cost, locally available materials to promote sustainability and practical applicability.

- To study the basic principles of evaporative cooling and analyze its advantages over conventional vapor-compression cooling systems.
- To design and develop a direct evaporative cooling system using honeycomb cellulose pads and porous pottery (terracotta) tubes as the primary cooling and filtration media.
- To develop the complete system architecture, including the air inlet section, cooling media arrangement, water circulation system, air-moving device, and air outlet section.
- To prepare detailed block diagrams and system architecture diagrams representing the airflow
- path, water distribution network, and component interconnections.
- To fabricate or assemble a laboratory-scale experimental setup based on the proposed design for performance evaluation.
- To analyze the working principle of the system based on adiabatic evaporation and interaction of air with wetted porous surfaces.
- To experimentally evaluate cooling performance by measuring inlet and outlet air temperature, temperature reduction, relative humidity variation, and cooling effectiveness.
- To investigate the ability of the wetted porous media to reduce particulate matter present in the air stream.
- To study the effect of operating parameters such as airflow rate and water circulation rate on system performance.
- To evaluate the energy consumption of the system considering the power required by the fan or blower and water circulation pump.
- To compare the performance of the proposed system with conventional cooling approaches in terms of energy efficiency and environmental impact.
- To identify suitable application areas such as industrial exhaust cooling, agricultural environments, and sustainable building ventilation systems.
- To include system photographs, schematic diagrams, and experimental setup figures for clear representation and understanding of the system.
- To limit the study to short-term experimental analysis, excluding long-term durability testing, detailed economic analysis, and advanced control strategies.

2. EXPERIMENTAL METHODOLOGY

The experimental methodology adopted in this study is aimed at evaluating the cooling performance, particulate matter reduction capability, and energy efficiency of the proposed sustainable direct evaporative cooling system. A laboratory-scale experimental setup was designed and developed based on the proposed system architecture. The experiments were conducted under controlled conditions to ensure repeatability and accuracy of results. The methodology includes system preparation, instrumentation, operating procedure, and data collection.

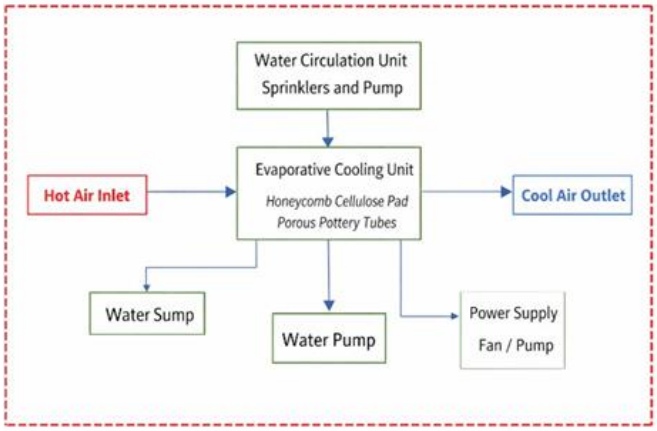


Figure 1: System Architecture

A. Experimental Setup

The experimental setup consists of a direct evaporative cooling unit incorporating a honeycomb cellulose cooling pad followed by porous pottery tubes arranged in a staggered configuration. A water circulation system comprising a water sump, pump, distribution piping, and sprinkler nozzles is used to ensure uniform wetting of the cooling pad and pottery tubes. Hot ambient air is allowed to pass through the wetted cooling media, enabling heat transfer through the evaporative process. Inlet and outlet sections are provided for measuring air properties before and after cooling.

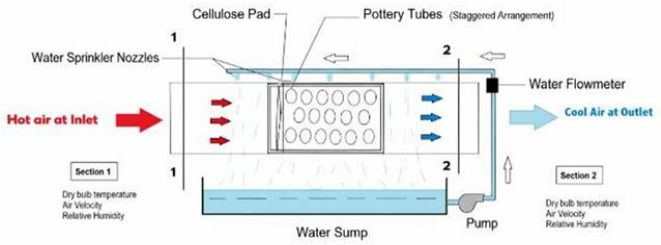


Figure 2: Schematic diagram of experimental setup

B. Instrumentation and Measuring Devices

The experimental setup is instrumented using a vision air quality meter and a digital thermo-hygrometer to measure the required parameters during experimentation. The vision air quality meter is used to monitor particulate matter levels and airflow-related parameters at the inlet and outlet sections of the system. The digital thermo-hygrometer is used to measure dry-bulb temperature and relative humidity of air at both locations.

All measurements are taken after the system reaches steady-state operating conditions to ensure accuracy and repeatability of results. The selected instruments provide adequate resolution and reliability for experimental performance evaluation of the proposed system.

C. Experimental Procedure

Before each experimental run, the water sump is filled to the required level and the pump is switched on to ensure proper wetting of the cooling pad and pottery tubes. After achieving steady operating conditions, inlet and outlet air parameters such as temperature, relative humidity, and air velocity are recorded.

Experiments are conducted for different operating conditions by varying water flow rate and airflow rate. Each test is repeated multiple times to minimize experimental uncertainty.



Figure 3: Set Up

D. Performance Parameters Evaluated

The performance of the proposed system is evaluated using the following parameters:

- Inlet and outlet air temperature
- Temperature reduction across the system
- Variation in relative humidity
- Cooling effectiveness
- Energy consumption
- Qualitative assessment of particulate matter reduction.

E. Data Analysis

The experimental data obtained from the performance evaluation of the proposed evaporative cooling system were systematically recorded, tabulated, and analysed to assess its thermal performance, particulate matter reduction capability, and energy efficiency under different operating conditions. Measurements

of inlet and outlet air temperature, relative humidity, and particulate matter concentration were collected after the system attained steady-state operation to ensure accuracy and repeatability. Multiple experimental runs were conducted for similar operating conditions, and average values were considered for analysis to minimize the effect of random errors.

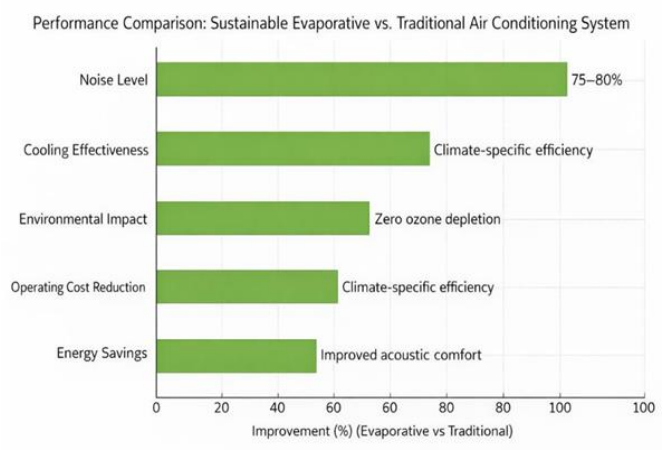
Cooling performance was analyzed by determining the temperature reduction across the system and evaluating cooling effectiveness using standard evaporative cooling relations based on inlet air conditions and outlet air temperature. The variation in relative humidity was also analyzed to understand the extent of moisture addition during the cooling process and to ensure suitability for ventilation and exhaust air treatment applications. The influence of operating parameters such as water circulation rate and airflow stability on cooling effectiveness was examined to identify performance trends.



Fig 4: Water spraying on pottery tubes

3. Results

The experimental study was carried out to evaluate the performance of the proposed sustainable direct evaporative cooling system in terms of air temperature reduction, variation in relative humidity, particulate matter reduction, and overall energy efficiency. All measurements were recorded at the inlet and outlet sections after the system attained steady operating conditions. The vision air quality meter and digital thermo-hygrometer were used to ensure consistent and repeatable data collection during experimentation. During system operation, a clear reduction in outlet air temperature was observed when compared to inlet air conditions. The temperature reduction was primarily attributed to the evaporation of water from the wetted honeycomb cellulose cooling pad and porous pottery (terracotta) tubes. Under hot and dry ambient conditions, the system produced a noticeable cooling effect, with the outlet air temperature consistently lower than the inlet temperature. The presence of terracotta tubes further enhanced the cooling performance by increasing air–water contact time and effective surface area, leading to improved heat transfer. In addition to temperature reduction, a moderate increase in relative humidity was observed at the outlet section. This increase is a characteristic behavior of direct evaporative cooling systems and confirms the occurrence of the evaporative process. However, the rise in humidity remained within acceptable limits for ventilation and exhaust air treatment applications. Stable humidity trends were observed across multiple experimental runs, indicating consistent system performance under similar operating conditions. The particulate matter reduction capability of the system was evaluated using the vision air quality meter. Observations showed a visible decrease in particulate concentration at the outlet compared to the inlet. This reduction occurred due to the interaction of air with wetted porous surfaces, where particulate matter was captured and removed through water- based deposition mechanisms.



Graph 1: Performance Comparison between Traditional air conditioning Vs sustainable evaporative cooling system

Accumulation of particulate matter in the water sump during extended operation further supported the effectiveness of the system in improving air quality. System performance was found to be influenced by operating conditions such as water circulation rate and airflow stability. Adequate wetting of the cooling pad and pottery tubes resulted in improved cooling effectiveness and more consistent particulate matter reduction. Insufficient water distribution led to reduced performance, highlighting the importance of uniform wetting of the porous media. Repeated experimental runs showed similar trends, indicating reliable and repeatable system behavior.

The energy consumption of the proposed system was observed to be significantly lower than that of conventional vapor-compression cooling systems. Electrical energy was primarily consumed by the water circulation pump, with no requirement for high- power components. As a result, the system demonstrated substantial potential for energy savings while providing effective cooling and air quality improvement. These results confirm that the proposed evaporative cooling system offers a sustainable and energy-efficient solution suitable for applications such as industrial exhaust air treatment, agricultural environments, and building ventilation.

4. Concluding Remarks

This technical report presented the design, development, and experimental evaluation of a sustainable direct evaporative cooling system aimed at providing effective thermal management along with particulate matter reduction. The system utilizes honeycomb cellulose cooling pads and porous pottery (terracotta) tubes to enhance evaporative heat transfer while simultaneously improving air quality through water-based particulate capture Experimental observations confirmed that the proposed system is capable of producing a significant reduction in air temperature under hot and dry climatic conditions with minimal energy consumption. The increase in relative humidity at the outlet remained within acceptable limits, making the system suitable for ventilation and exhaust air treatment applications. The use of wetted porous media proved effective in reducing particulate matter concentration, demonstrating the dual functionality of cooling and air purification.

Compared to conventional vapor-compression air-conditioning systems, the proposed setup operates with substantially lower power requirements, as electrical energy is consumed only by the water circulation pump. This results in considerable energy savings, reduced operating costs, and elimination of environmentally harmful refrigerants. The simplicity of the system, use of locally available materials, and low maintenance requirements further enhance its economic and practical feasibility.

Overall, the sustainable evaporative cooling system offers an eco-friendly, energy-efficient, and cost-effective alternative for applications such as industrial exhaust cooling, agricultural environments, and building ventilation. Future scope of work includes long-term performance evaluation, optimization of cooling media arrangement, and integration with renewable energy sources to further enhance system sustainability.

References

1) R. K. Rajput, Heat and Mass Transfer, 5th ed. New Delhi, India: S. Chand, 2018.
2) A. P. Kulkarni and S. P. Rajput, "A review on evaporative cooling systems," Renewable and Sustainable Energy Reviews, vol. 16, no. 5, pp. 3300–3312, 2012.
3) J. R. Camargo, C. D. Ebinuma, and J. L. Silveira, "Experimental performance of a direct evaporative cooler," Energy Conversion and Management, vol. 46, no. 13–14, pp. 2187–2198, 2005.
4) S. Jain and D. G. Hindoliya, "Experimental performance of new evaporative cooling pad materials," Energy and Buildings, vol. 43, no. 9, pp. 2522–2528, 2011.
5) A. A. Watt, Evaporative Air Conditioning Handbook, 2nd ed. New York, NY, USA: McGraw- Hill, 1986.
6) S. Windnigda, A. Kumar, and P. Singh, "Performance analysis of terracotta-based evaporative cooling systems," Procedia Structural Integrity, vol. 51, pp. 312–319, 2024.
7) M. Riffat and X. Zhao, "Review of heat recovery technologies for building applications," Energy and Buildings, vol. 36, no. 5, pp. 453–469, 2004.
8) ASHRAE, ASHRAE Handbook HVAC Systems and Equipment. Atlanta, GA, USA: ASHRAE, 2020.
9) U.S. Environmental Protection Agency, "Particulate matter (PM) pollution," EPA, Washington, DC, USA, Tech. Rep., 2022.
10) World Health Organization, "Health effects of particulate matter: Policy implications," WHO Press, Geneva, Switzerland, 2013.
11) S. Heliyon, "Environmental impact of air pollution and particulate matter," Heliyon, vol. 6, no. 9, Art. no. e04919, 2020.
12) P. V. Nielsen, "Control of airborne contaminants in ventilated spaces," Indoor Air, vol. 14, no. 7, pp. 98–110, 2004.
13) S. A. Nada and A. M. Elattar, "Energy and environmental assessment of cooling systems," Applied Thermal Engineering, vol. 31, no. 17–18, pp. 3479–3486, 2011.