

Research Article

Experimental Investigation of a Direct Evaporative Cooling System for Year-Round Thermal Management with Solar-Assisted Dryer

Sujatha Abaranji ¹, Karthik Panchabikesan ², and Velraj Ramalingam ³

¹Department of Mechanical Engineering, Thanthai Periyar Government Institute of Technology, Vellore, 632002 Tamil Nadu, India

²Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada

³Department of Mechanical Engineering, Institute of Energy Studies, Anna University, Chennai, 600025 Tamil Nadu, India

Correspondence should be addressed to Sujatha Abaranji; asujatha.06@gmail.com

Received 14 October 2020; Revised 14 November 2020; Accepted 21 November 2020; Published 19 December 2020

Academic Editor: Kumarasamy Sudhakar

Copyright © 2020 Sujatha Abaranji et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Building cooling is achieved by the extensive use of air conditioners. These mechanically driven devices provide thermal comfort by deteriorating the environment with increased energy consumption. To alleviate environmental degradation, the need for energy-efficient and eco-friendly systems for building cooling becomes essential. Evaporative cooling, a typical passive cooling technique, could meet the energy demand and global climatic issues. In conventional direct evaporative cooling, the sensible cooling of air is achieved by continuous water circulation over the cooling pad. Despite its simple operation, the problem of the pad material and water stagnation in the sump limits its usage. Moreover, the continuous pump operation increases the electrical energy consumption. In the present work, a porous material is used as the water storage medium eliminating the pump and sump. An experimental investigation is performed on the developed setup, and experiments are conducted for three different RH conditions (low, medium, and high) to assess the porous material's ability as a cooling medium. Cooling capacity, effectiveness, and water evaporation rate are determined to evaluate the direct evaporative cooling system's performance. The material that replaces the pump and sump is vermicompost due to its excellent water retention characteristics. There is no necessity to change material each time. However, the vermicompost is regenerated at the end of the experiment using a solar dryer. The passing of hot air over the vermicompost also avoids mould spores' transmission, if any, present through the air. The results show that vermicompost produces an average temperature drop of 9.5°C during low RH conditions. Besides, vermicompost helps with the energy savings of 21.7% by eliminating the pump. Hence, vermicompost could be an alternate energy-efficient material to replace the pad-pump-sump of the conventional evaporative cooling system. Further, if this direct evaporative cooling system is integrated with solar-assisted drying of vermicompost, it is possible to provide a clean and sustainable indoor environment. This system could pave the way for year-round thermal management of building cooling applications with environmental safety.

1. Introduction

The rapid population growth has attributed to the drastic rise in energy consumption. The critical factor driving energy consumption is the weather effect, which leads to an increase in cooling and heating requirements to provide thermal comfort. Air conditioners play a vital role in providing thermal comfort to the occupants of the building. The continuous

operation of these devices increased greenhouse gas emissions. The rise in emissions directly related to energy demand poses a severe threat to the environment. In the current scenario, sustainable and energy-efficient technologies would be convincing to provide a clean and safe ecosystem. Since ancient times, passive cooling techniques have provided comfortable living space without any emissions. Moreover, the use of renewable energy sources could reduce energy

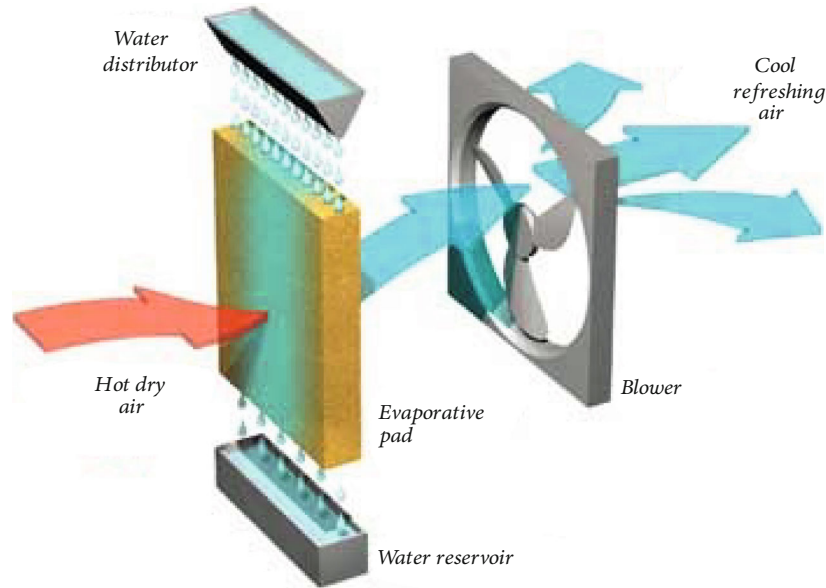


FIGURE 1: Conventional pad pump system [1].

TABLE 1: Research work carried out for different climates.

Authors	System type	Building type	Region	Climate	Key findings
Costelloe and Finn [11]	Indirect contact evaporative cooling system	Office buildings	Dublin and Milan	Temperate	As a consequence of 16°C cooling water from October to May, the office buildings in Dublin can be cooled throughout the year without the use of conventional cooling. In Milan, a similar performance can be achieved from November to March
Heidarinejad et al. [12]	Two-stage indirect-direct evaporative cooling system	Public buildings	Tehran	Multi	Two-stage indirect-direct evaporative cooling system can be preferred to mechanical vapour compression systems in regions with higher wet-bulb temperatures to minimise energy consumption. However, water consumption of the two-stage system is 55% greater than that of traditional DEC
Ibrahim et al. [13]	Direct evaporative cooling system equipped with porous ceramic evaporators	Residential buildings	Nottingham	Multi	Direct evaporative cooling system supported with porous ceramic evaporators can provide 6–8°C in dry-bulb temperature with a 30% rise in relative humidity. The maximum cooling achieved from the system is 224 W/m ²
Hajidavalloo [14]	Indirect contact evaporative cooling system	Residential buildings	Khoozestan, Iran	Very hot	Through this system, power consumption can be decreased by about 16% in very hot climates, and the COP can be enhanced by 55% compared to conventional air conditioners
He and Hoyano [15]	Passive evaporative cooling wall (PECW)	Residential courtyards	Japan	Hot and dry	PECW constructed as ceramic pipes absorb water using capillary action. It can reduce the surface temperature of the pipe by 3–5°C than the ambient, and the ambient air temperature is dropped to 3–4°C
Katsuki et al. [16]	Porous ceramic plates	—	Korea	Hot and dry	The study reports that porous properties and relative humidity of air are the key factors influencing the self-cooling effect of porous ceramic plates

demand. Hence, passive cooling integrated with renewable energy sources could be the best alternative to meet conventional mechanically driven equipment's challenges.

Evaporative cooling, a passive cooling method, had been in use since 2500 B.C. An evaporative cooler makes use of water to cool the hot and dry air. The water takes up the air's

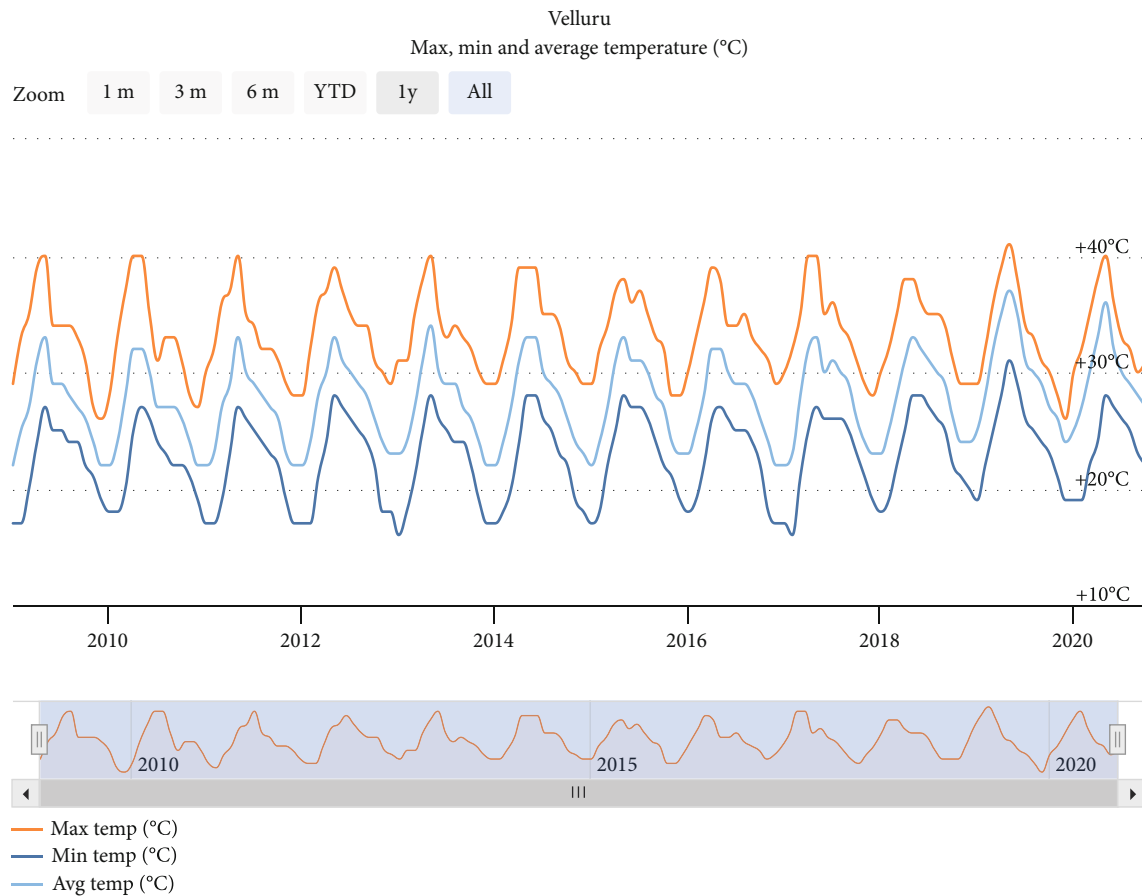


FIGURE 2: Yearly temperature average of Vellore from 2009 to 2019 [19].

sensible heat and gets evaporated to produce cold and humid air. It takes shape in several forms, and the modern evaporative coolers consist of a pad-pump system with a reservoir to recirculate the water. The working principle of a direct evaporative cooling system is shown in Figure 1.

Evaporative cooling pads are generally made of cellulose materials. These materials are used in desert air coolers due to their excellent cooling performance with high durability. However, its high cost limits its utility to higher-end coolers. Cellulose impregnated cooling pads were employed for different studies. Rong et al. [2] studied the dynamic performance of a cross-fluted cellulose pad by controlling the pump's on and off time (control time cycle), water flow rate, etc. A relationship between cooling efficiency and the water-air ratio was one of the useful parameters for the controller. This prediction model for transient conditions provides the solution for poultry houses' control systems in a hot-arid climate. Xu et al. [3] developed an evaporative cooling setup with corrugated cellulose pads to provide thermal comfort for greenhouses in a humid subtropical climate. Evaporative coolers made of cellulose pads were combined with air conditioners and tested by Harby and Al-Amri [4] and Dhamneya et al. [5] to study their performance in achieving energy savings of a split air conditioner and window air conditioner, respectively. Aspen cooling pads were preferred in some air coolers due to their lower cost and effectiveness. Bishoyi

and Sudhakar [6] compared the performance of aspen and honeycomb cooling pads. The results had shown that the honeycomb cooling pad achieved the highest effectiveness compared with the aspen cooling pad.

Many natural and synthetic fibres and other materials were also tested for their suitability to be used as a cooling pad material. Al-Sulaiman [7] proposed an experimental setup to evaluate the cooling pads' performance made from the fibres of date palm (stem), luffa, and jute. The results were compared with a commercially available cooling pad. The results showed that the highest effectiveness of 62.1% was obtained for jute material, while the conventional cooling pad material gave 49.9% effectiveness. Dođramacı et al. [8] used eucalyptus fibres as cooling pad material and showed that these fibres perform better in cooling efficiency at lower velocities. Jain and Hindoliya [9] tested the effectiveness of a cooling pad with coconut and palash fibres and compared them with a conventional pad made of aspen and khus fibres. The palash fibres offered a low pressure drop than the aspen pad, and its effectiveness was comparatively higher.

Many researchers tested different evaporative cooling systems for their local climatic conditions. Cuce and Riffat [10] presented the types of evaporative cooling systems, thermodynamic analyses, thermal performance assessment, and their applications in buildings. The different types of direct and indirect evaporative cooling are employed in the cooling

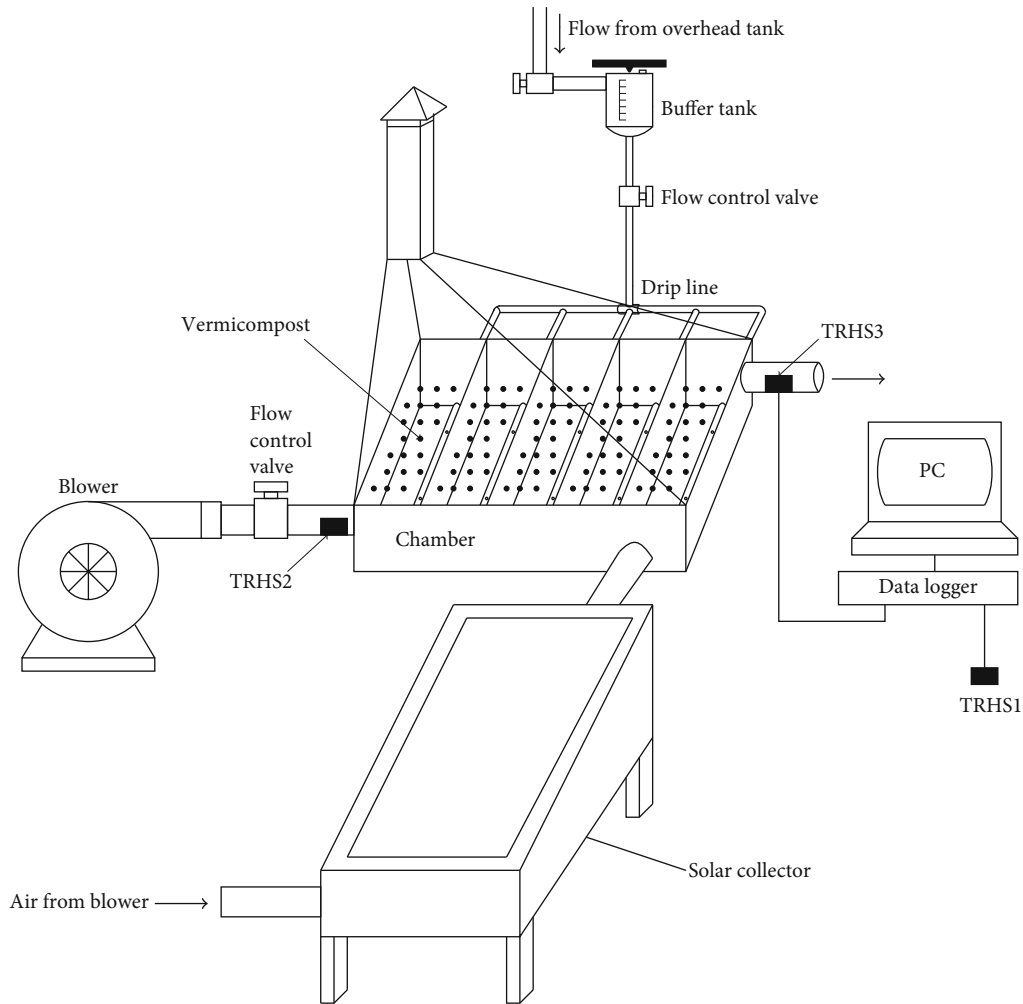


FIGURE 3: Schematic of the experimental setup. TRHS: temperature and relative humidity sensor.



FIGURE 4: Photographic view of the cooling chamber loaded with vermicompost.

system based on humidity conditions. Based on the building's cooling load requirement, novel evaporative cooling systems were tested for different climatic conditions and are presented in Table 1.

From the extensive literature, it is understood that evaporative cooling, which is quite simple and inexpensive, is suitable for hot and dry climates. However, the pad material is subjected to problems like sagging, clogging, and scaling. Watt [17] had addressed these problems, which led to the deterioration of pad material and reduced its life. The continuous operation of the pump increases the electrical energy



FIGURE 5: Photographic view of the solar collector.

consumption. The reservoir, which stores the water for recirculation, provides a favourable environment for breeding disease-spreading insects. In the present work, a porous material—vermicompost is used to replace the pad, pump, and reservoir. Vermicompost is highly porous with high water storing capability [18]. The specific objective of the system is to study the performance of vermicompost based

TABLE 2: Specifications of the measuring instruments.

Instrument	Parameter	Device	Range	Accuracy
Load cell	Mass of vermicompost	Load cell module ITB-04CE	0-5 kg	1.5% of full-scale division
Digital vane anemometer	Velocity of air	Lutron AM4201	0.4 ms ⁻¹ to 30 ms ⁻¹	±2%
Digital hygro thermometer	Temperature and RH of air	DHT 22	Temp: -40°C to 80°C RH: 0% to 100%	Temp: ±0.5°C RH: ±2%

direct evaporative cooling system with three different velocities (0.9 ms⁻¹, 1.8 ms⁻¹, and 2.7 ms⁻¹) under different relative humidity conditions of ambient air (high, medium, and low). The water retention ability of vermicompost is evaluated in terms of evaporative cooling capacity, effectiveness, and water evaporation rate. Thus, vermicompost's cooling potential for use in direct evaporative cooling to provide a sustainable and clean indoor environment for year-round thermal management is explored in this work.

2. Materials and Methodology

2.1. Vermicompost: An Alternative Material for Direct Evaporative Cooling. Vermicompost, a porous material with high water storage capacity, is extensively used in agriculture to promote plant growth during water stress conditions. Many scientists had studied the performance of evaporative cooling systems with porous materials. However, vermicompost, which possesses high porosity and high water retaining ability, is not explored yet, as a cooling medium in the evaporative cooling system. The problems of continuous pump operation and water stagnation in the sump are to be eliminated using vermicompost as a water storage medium. Vermicompost loaded in the system can be used again, and there is no necessity to change material each time. However, the vermicompost should be regenerated at the end of each cycle to sterilize the material from the mould growth. Vermicompost drying is achieved using an indirect solar dryer. The hot air from the solar collector dries the vermicompost.

2.2. Site Selection. The outstanding performance of evaporative coolers in arid regions facilitated to test the vermicompost as a cooling medium in a direct evaporative cooling system at Vellore, an Indian city with hot and dry weather. The yearly average temperature history of Vellore from 2009 to 2019 is shown in Figure 2. The average temperature throughout the year is 30°C ± 5°C. The maximum temperature of 42°C and minimum temperature of 19°C are almost reached every year. This temperature history indicates that Vellore weather conditions have great potential for evaporative cooling throughout the year.

2.3. Experimental Investigation. This section describes the experimental setup and the operational procedures adopted to evaluate the performance of the vermicompost.

2.3.1. Experimental Setup Description. Figure 3 shows a vermicompost-based evaporative cooling system integrated with an indirect solar dryer. The experimental setup consists of a cooling chamber tray with a baffle arrangement, air blower, buffer tank of 0.5-liter capacity to supply water, the

TABLE 3: Uncertainties in measured parameters and evaluated parameters.

<i>Measured parameters</i>	
Temperature	1.51%
Relative humidity	4.83%
Air velocity	2.22%
<i>Evaluated parameters</i>	
Effectiveness	0.88%
Evaporative cooling capacity	2.28%

monitoring sensors, and instruments with a data acquisition system. The cooling chamber tray is made of a rectangular box of 400 × 300 × 100 mm for charging the vermicompost. The tray consists of five baffle plates with perforations at the end to create turbulence in the flowing air. The photographic view of the cooling chamber loaded with vermicompost is shown in Figure 4. A centrifugal blower of 180 W capacity forces the air into the cooling chamber through a galvanized iron pipe of 25.4 mm diameter. A flow control valve is provided after the blower for varying the velocity of air. Water is supplied to the vermicompost through small tubes of 4 mm diameter. An insulation material (polyurethane foam) of 5 mm thickness is provided over the entire setup to avoid heat entry from the ambient to the cooling system. The vermicompost in the cooling chamber is dried with a solar dryer. The solar dryer consists of a solar collector to receive the radiation. It has an aluminium absorber plate, glass cover, plywood, and insulation material. Figure 5 shows the photographic view of the solar collector. Asbestos is used as the insulation material at the bottom of the absorber. The absorber plate is coated with black paint to enhance solar absorption. The absorber area is 0.4 m². A chimney of 300 mm height is used for discharging the air after drying the vermicompost in the chamber. Temperature and relative humidity sensors (DHT 22) are placed at three locations of the setup. DHT 22 uses a capacitive-type sensor for humidity measurement and a thermistor for temperature measurement. The sensor (TRHS1) used for measuring the ambient conditions is kept exposed to the atmosphere on the outer surface of the setup. TRHS2 placed at 30 mm before the entry of the chamber and TRHS3 located 30 mm after the exit of the chamber measure the temperature and RH of air entering and leaving the chamber, respectively. The measurements are made continuously at a scanning rate of 1 minute using a data acquisition system (Agilent Keysight, Model no. 34972A). The details of the instruments used for measurement are presented in Table 2.

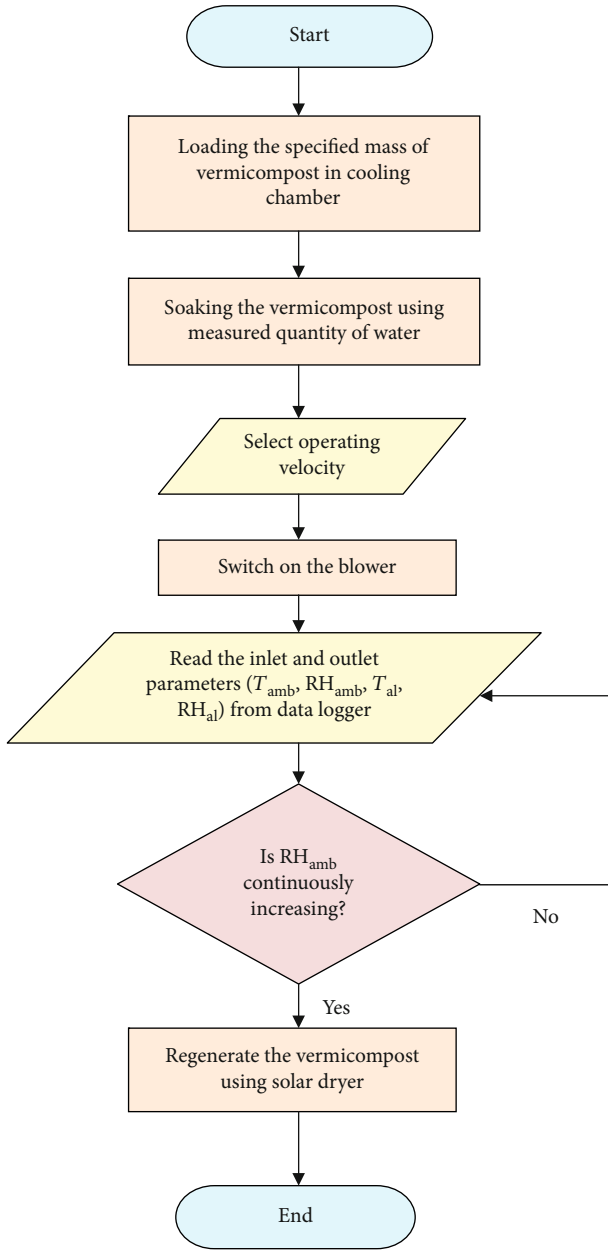


FIGURE 6: Flowchart of the methodology of the experimental analysis.

The parameters measured directly using the instruments are used to obtain the derived parameters of interest. Table 3 presents the uncertainties of the parameters which were measured directly using instruments and the evaluated parameters using the rules of error propagation suggested by Taylor [20].

2.3.2. Experimental Procedure. Cattle manure-based vermicompost was dried before its use in the cooling system. A known quantity of vermicompost (1000 grams) was measured using the load cell. The material was loaded in the cooling chamber. Initially, trial experiments were conducted for various water quantities to find the vermicompost's maxi-

imum water holding capacity. It was found that with the vermicompost : water mass ratio of 100 : 75, the material attained fully saturated condition. Then, water was supplied to the vermicompost in the above ratio until its saturation. No additional water was provided during the operation of the system. The blower was switched on to allow the air to pass over the vermicompost, and the flow control valve was adjusted to set the desired velocity of 0.9 ms^{-1} . Usually, direct evaporative coolers are not operated with air velocity exceeding 3 ms^{-1} to avoid aerosols' formation [21]. The temperature and relative humidity were measured by the sensors placed at different locations and were recorded continuously. The same procedure was repeated for other velocities of 1.8 ms^{-1} and 2.7 ms^{-1} . The same material can be used again, and there is no necessity to change material each time. However, the vermicompost is regenerated at the end of the experiment using a solar dryer. The passing of hot air over the vermicompost also avoids mould spores' transmission, if any, present through the air. The experiments were conducted during October 2019, February 2020, and May 2020 for high RH, medium RH, and low RH conditions. Direct evaporative coolers are employed in places with hot and dry weather to provide cooling during peak sunshine hours (11 a.m. to 3 p.m.). In Vellore, where the experiments were conducted, three distinct seasons could be observed in a year (peak summer, winter, and monsoon season). Hence, three months were selected that represent the above three seasons. Accordingly, it is found that in September, the RH value is high in the range of 60% to 75%; in February, the RH is in the midrange of 45% to 60%; and in May, the RH value is low in the range of 30% to 45%. The duration of the experiments was 180 minutes, 360 minutes, and 480 minutes for high, medium, and low RH conditions, respectively. Though all the experiments were started at 10 a.m., the experiments were terminated when there was an appreciable change in ambient RH during certain months. However, it was continued till 6 p.m. in May (peak summer month) when the low ambient RH existed till late evening. Since the end of the experiment varied in different months, the experiments' duration also varied.

Figure 6 shows the detailed methodology of the experimental analysis in a flowchart form.

3. Data Analysis

This section explains the formulae used for calculating the following derived parameters: evaporative cooling capacity, effectiveness, and evaporation rate of water.

3.1. Evaporative Cooling Capacity. The evaporative cooling capacity is calculated using the following equation:

$$Q_{ec} = \dot{m} c_p (T_{amb} - T_{al}). \quad (1)$$

3.2. Effectiveness. Effectiveness is one of the key factors in evaluating the evaporative cooler performance. The ratio of temperature difference of inlet air and outlet air to the temperature difference of inlet air and its wet-bulb temperature is called effectiveness.

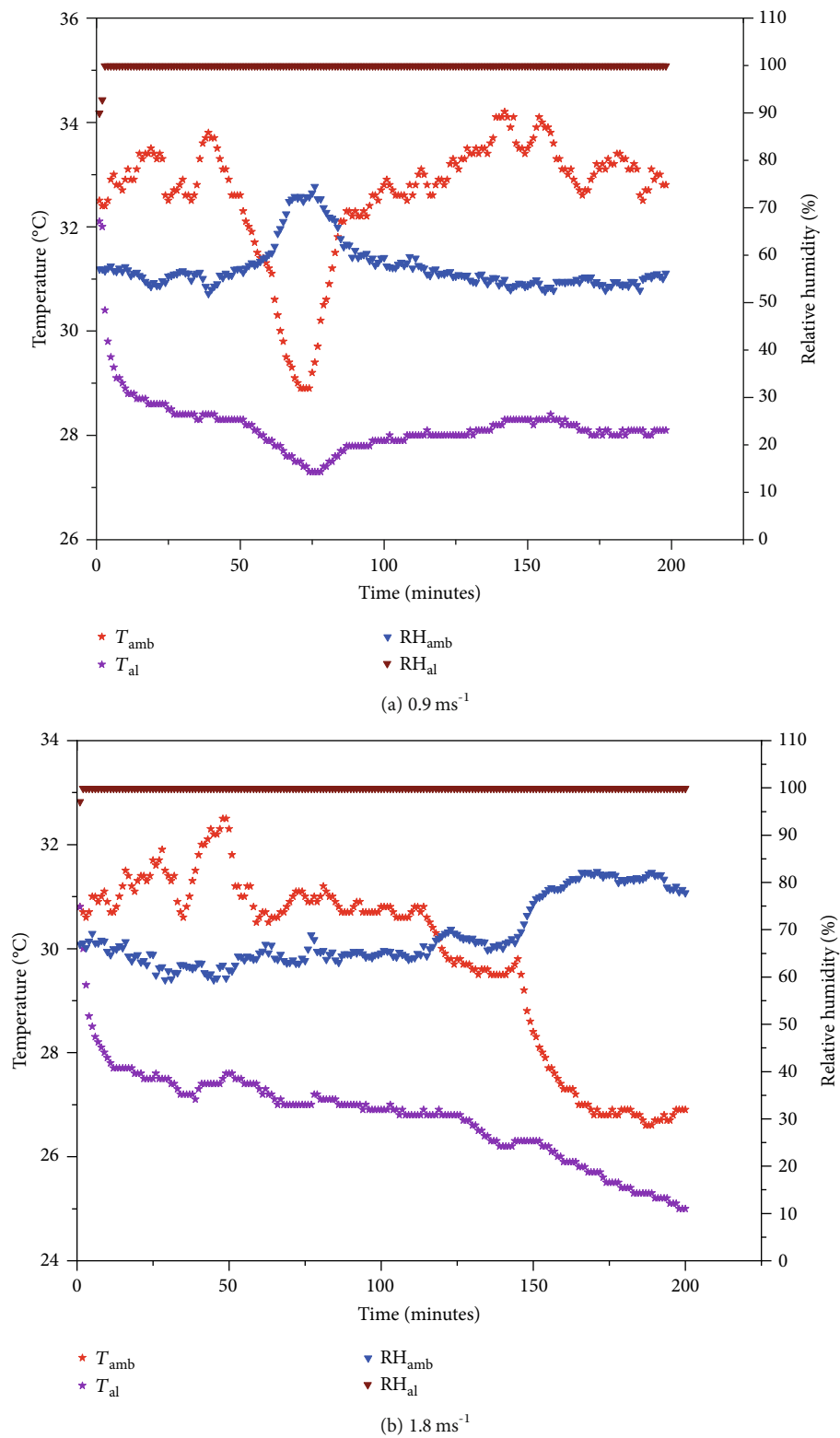


FIGURE 7: Continued.

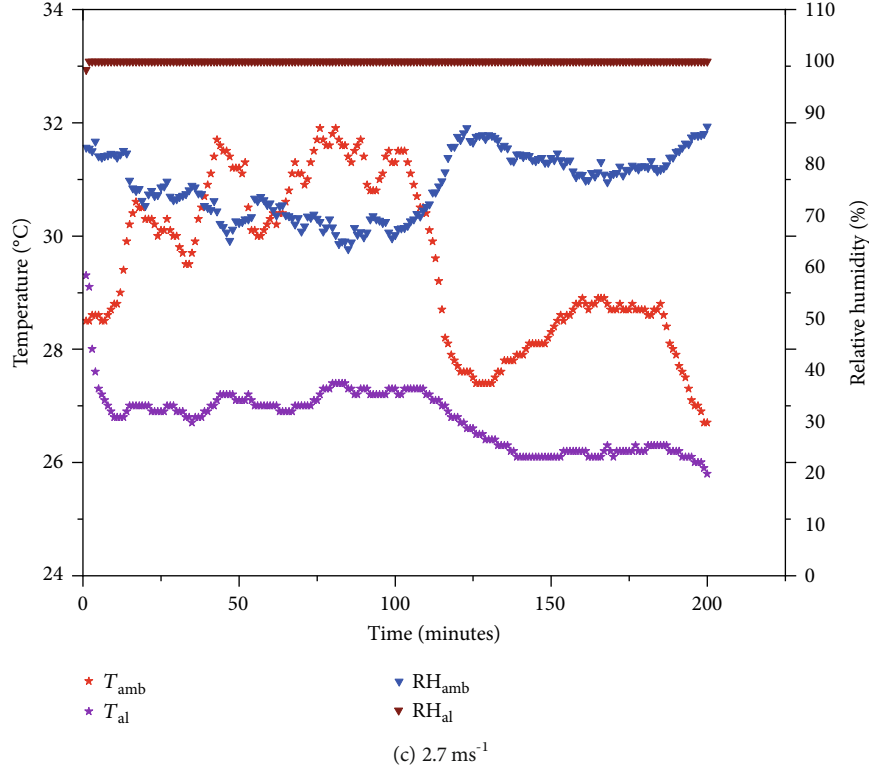


FIGURE 7: Temperature and RH variations of the air from the air cooler at three different velocities under high RH condition.

It is given by

$$\varepsilon = \frac{T_{\text{amb}} - T_{\text{al}}}{T_{\text{amb}} - T_{\text{wbt}}} \quad (2)$$

3.3. *Evaporation Rate of Water.* The amount of water required to produce the cooling effect is calculated using the formula given by

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) \quad (3)$$

4. Results and Discussion

In this section, the variations of temperature and relative humidity of air are initially presented, followed by the discussion of derived parameters such as evaporative cooling capacity, effectiveness, and evaporation rate of water. Subsequently, the temperature drop and effectiveness of the previous studies are compared with the present system.

4.1. *Variations in Temperature and Relative Humidity of the Air.* Figure 7 shows the temperature and relative humidity of ambient air and outlet air from the cooling chamber when the air was supplied at three different velocities for high RH conditions.

It is seen from the figures that the ambient conditions play a significant role in deciding the performance of the cooling system. In Figure 7(a), the fluctuations of the temperature and relative humidity of ambient air were quite small

except for a short duration. A sudden change in ambient conditions was observed after 150 minutes, as shown in Figure 7(b), and 100 minutes, as shown in Figure 7(c). However, the average drop in temperature was 4°C to 5°C for all velocities up to 150 minutes. The outlet relative humidity is 99%, as the ambient relative humidity varied from 60% to 75%. It is also found from the figures that when the system is operated at lower velocities, maximum temperature drop was achieved with slight fluctuations. Moreover, the time taken to attain this condition is large. When the system was operated at higher velocities, the maximum temperature drop was achieved within a few minutes, and the same drop was sustained for a more extended period.

Figure 8 shows the temperature and relative humidity of ambient air and outlet air from the cooling chamber when the air was supplied at three different air velocities for medium RH conditions. It is seen in Figure 8(a) that the system produced an average temperature drop of 5°C for 60 minutes for a velocity of 0.9 ms⁻¹. After this, there was a continuous decrease in the temperature drop until the end of the experiment. For the operational velocity of 1.8 ms⁻¹, it is observed in Figure 8(b) that an average temperature drop of 7°C was produced until 150 minutes, followed by a gradual decrease in the temperature drop. Figure 8(c) shows that an average temperature drop of 8°C was produced by the system for 300 minutes when the system was operated at a velocity of 2.7 ms⁻¹. The outlet relative humidity produced by the system is 99% for all velocities.

It is inferred from the above results that an average temperature drop of 5°C to 8°C and a relative humidity of 99%

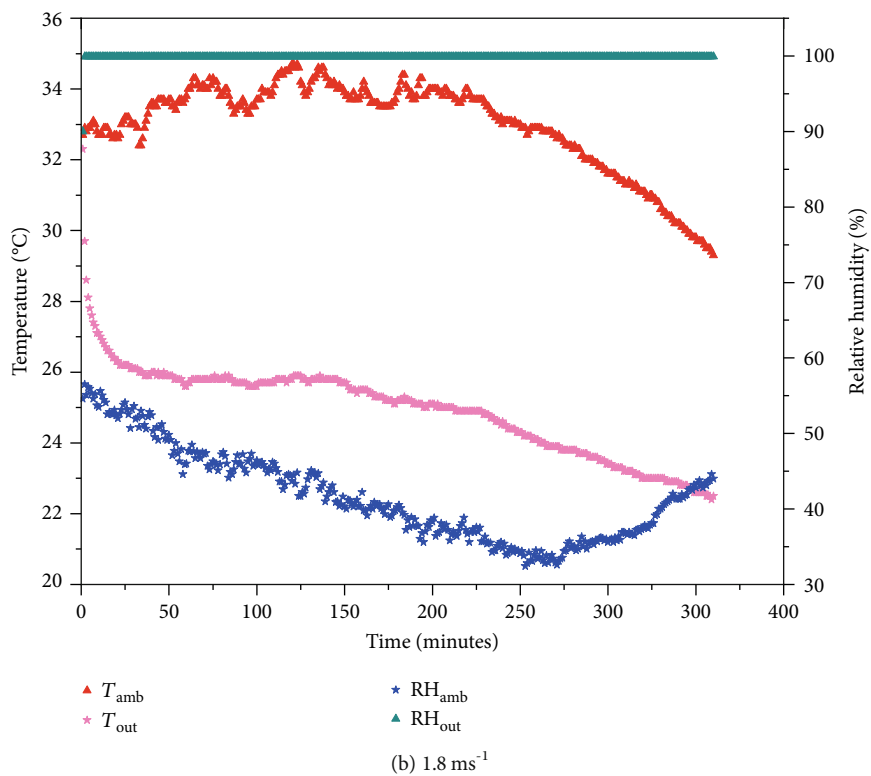
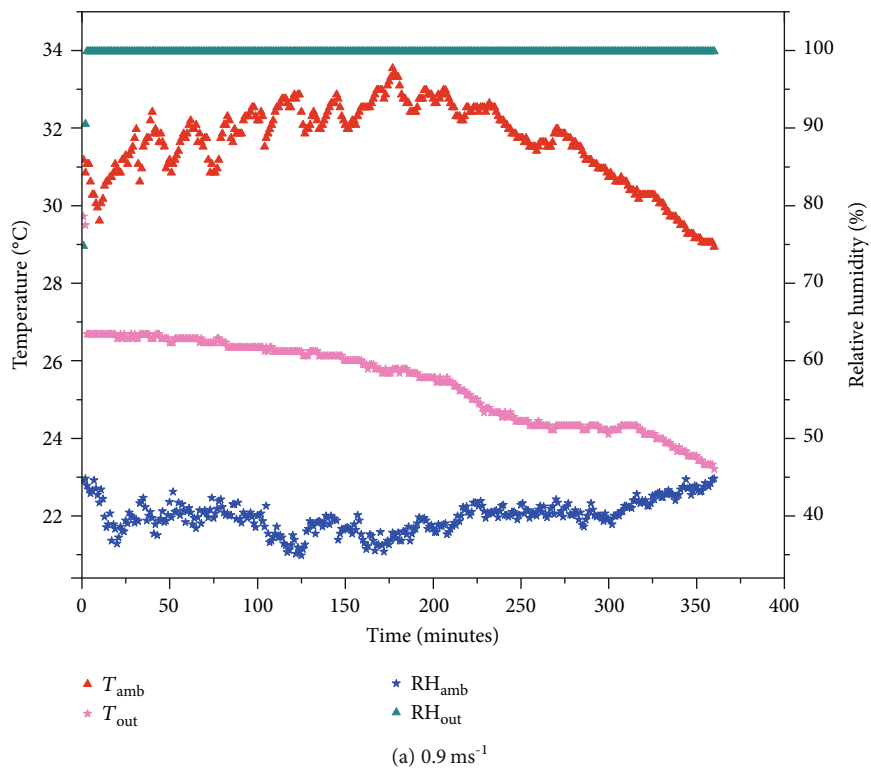


FIGURE 8: Continued.

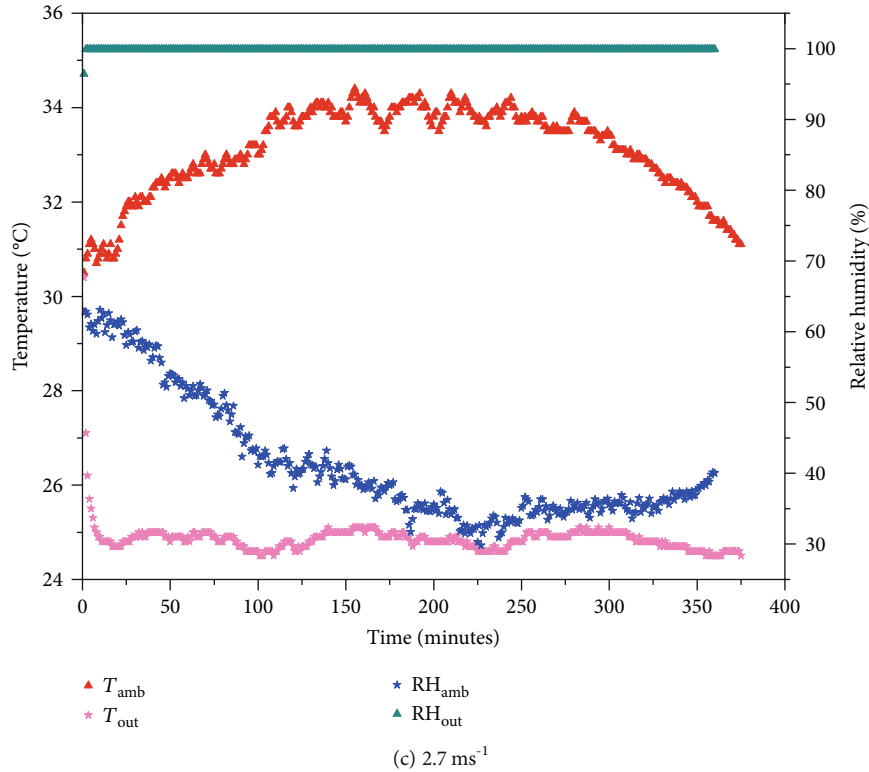


FIGURE 8: Temperature and RH variations of the air from the air cooler at three different velocities under medium RH condition.

could be achieved with this system based on the operating velocity if the ambient air has a temperature of 30°C to 34°C and relative humidity of 45% to 60%.

Figure 9 shows the temperature and relative humidity of ambient air and outlet air from the cooling chamber when the air was supplied at three different air velocities for low RH conditions. It is illustrated from the figures that the temperature drop produced by the vermicompost is maintained for a longer duration at all velocities during low RH conditions compared to other RH conditions. An average temperature drop of 6.5°C , 9.4°C , and 8.8°C was produced by the system up to 400 minutes when the system was operated at velocities of 0.9 ms^{-1} , 1.8 ms^{-1} , and 2.7 ms^{-1} , respectively. The relative humidity of air leaving the system is 99% for all velocities. It is inferred from the above results that an average temperature drop of 6.5°C to 9.5°C and relative humidity of 99% could be achieved with this system based on the operating velocity. The ambient air has a temperature of 38°C to 42°C and relative humidity of 30% to 45%.

Figure 10 shows the average temperature drop produced by the cooling system operated at three different velocities during three different RH conditions.

The above results elucidate that the vermicompost-based evaporative cooling system performs better at velocities of 1.8 ms^{-1} and 2.7 ms^{-1} during low and medium RH conditions. However, for high RH conditions, though the temperature drop produced by vermicompost at 0.9 ms^{-1} velocity is high, the time taken to achieve a higher reduction is more. At the same time, the system operated at higher velocities produces a maximum drop within a few minutes. Hence, it is clear that

ambient relative humidity and operating velocity are the key factors that influence the performance of a vermicompost-based evaporative cooling system.

4.2. Instantaneous Cooling Capacity. Figure 11 shows the instantaneous cooling capacity calculated using Equation (1) for three different velocities under three different RH conditions.

It is clear from the figures that the duration of sustained cooling effect varies based on the temperature drop for all velocities during different RH conditions. The period of sustainability is 120 minutes for high RH conditions, 300 minutes for medium RH conditions, and 400 minutes for low RH conditions.

Figure 12 shows the average instantaneous cooling capacity produced by the cooling system at three different velocities under three different RH conditions. It is seen from the figure that the system produces a higher cooling capacity for a velocity of 2.7 ms^{-1} during all RH conditions. It is also observed that there is a dependency between the mass flow rate and evaporative cooling capacity. The higher cooling rate could be achieved by increasing the airflow velocity and area of flow. Since the maximum velocity should be limited to 3 ms^{-1} to avoid health issues, the area of flow can be increased, and hence, mass flow rate can be increased. However, 1000 grams of vermicompost with the same mass flow rate is capable of producing a higher cooling effect during low RH conditions. This increases the amount of water to be evaporated for providing the required cooling effect. Hence, a large sump is needed for

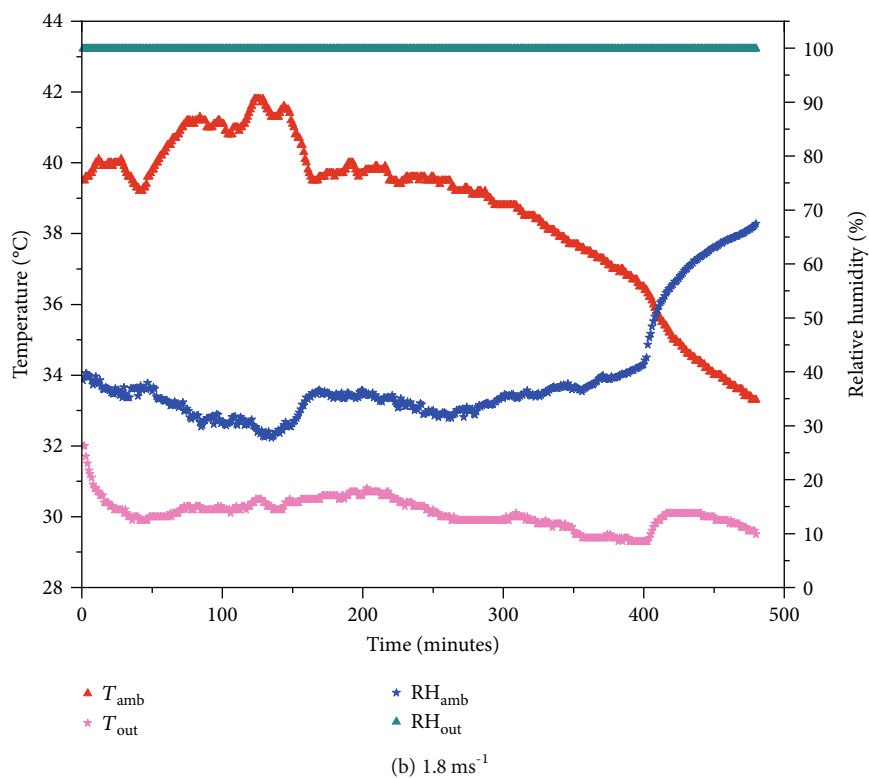
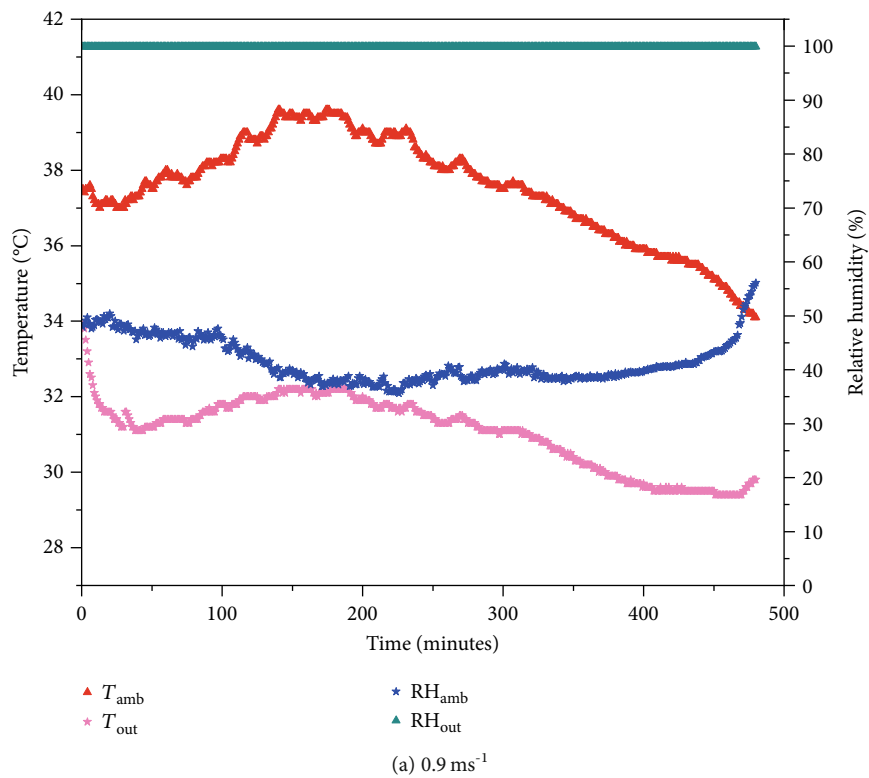


FIGURE 9: Continued.

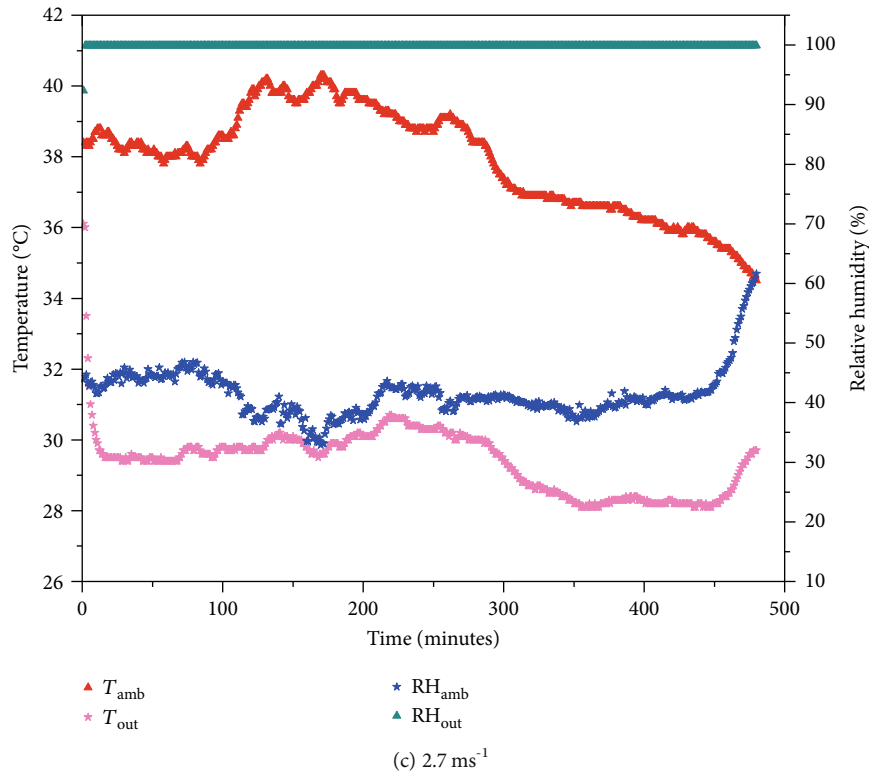


FIGURE 9: Temperature and RH variations of the air from the air cooler at three different velocities under low RH condition.

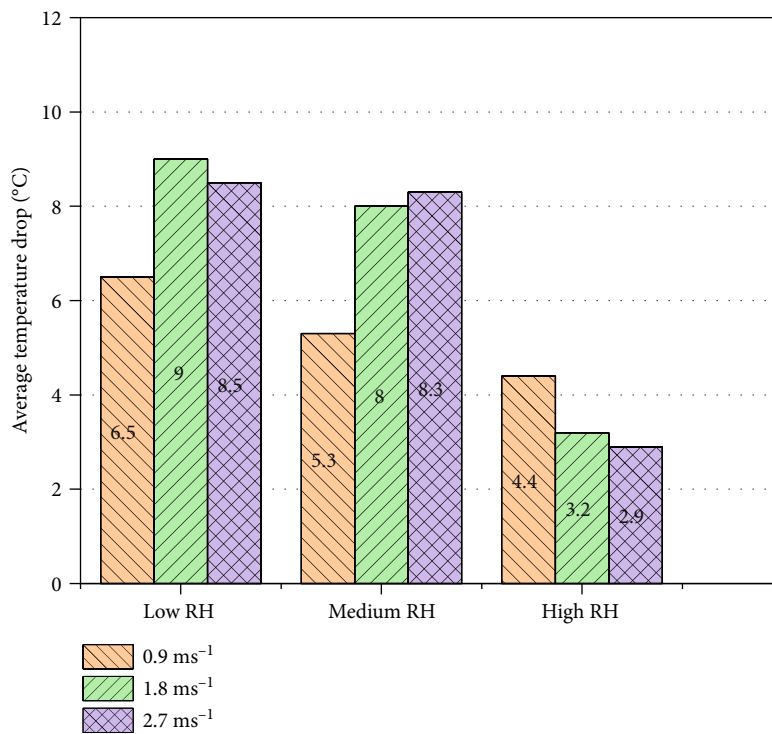
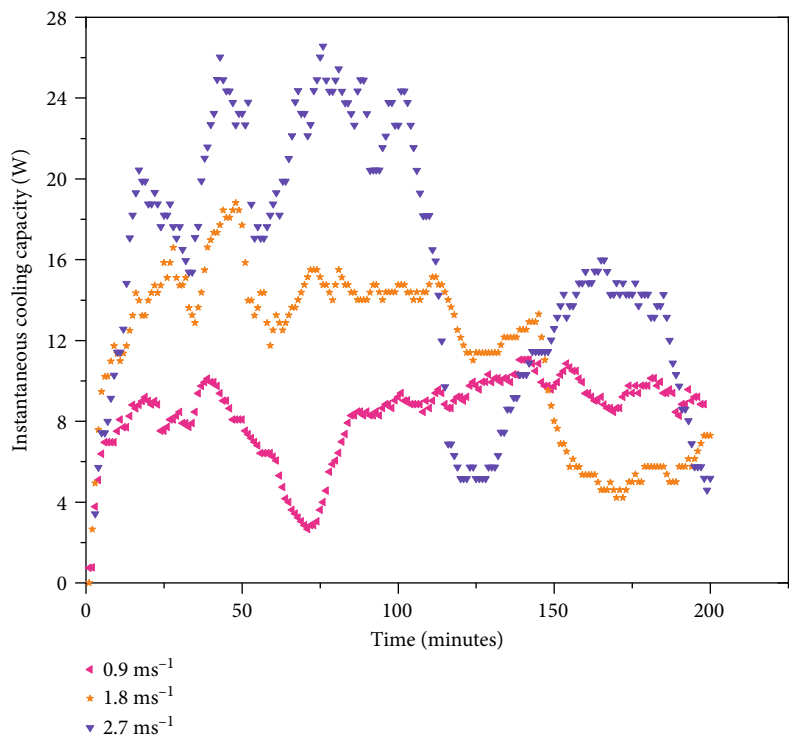


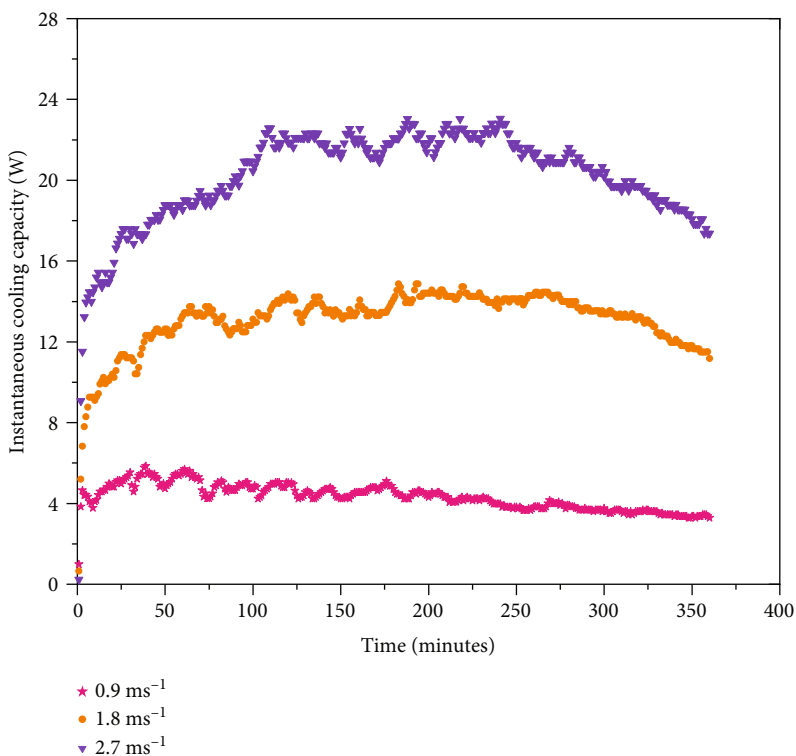
FIGURE 10: Average temperature drop of the air from the air cooler at three different velocities under three different RH conditions.

water storage. This vermicompost-based cooling system is producing the cooling effect by utilizing only the initial water supply and thus eliminating the water sump system

and related health issues. Hence, the vermicompost-based cooling system can produce sustained cooling at higher velocities during all RH conditions.

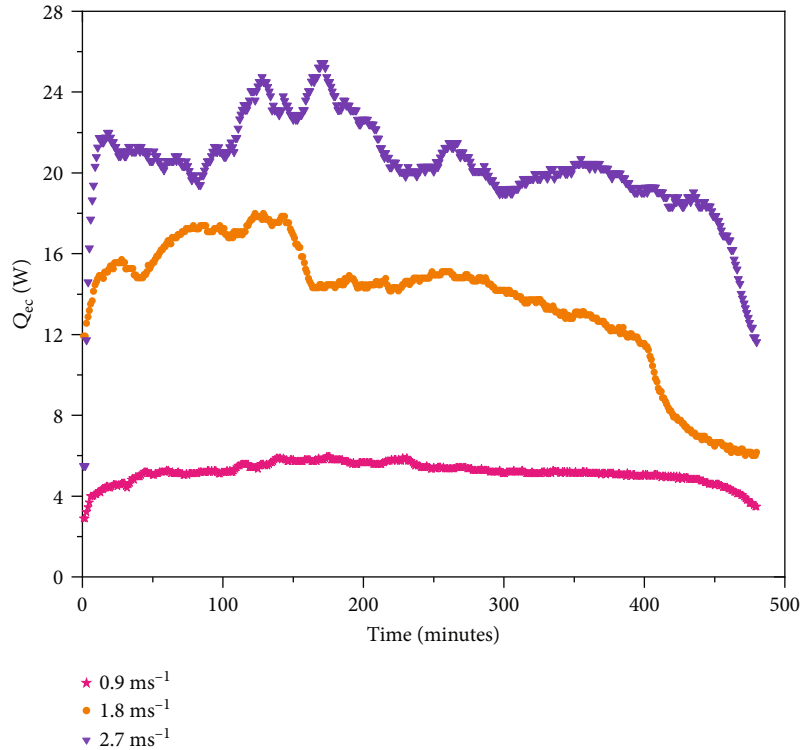


(a) High RH



(b) Medium RH

FIGURE 11: Continued.



(c) Low RH

FIGURE 11: Instantaneous cooling capacity of the air cooler at three different velocities under three different RH conditions.

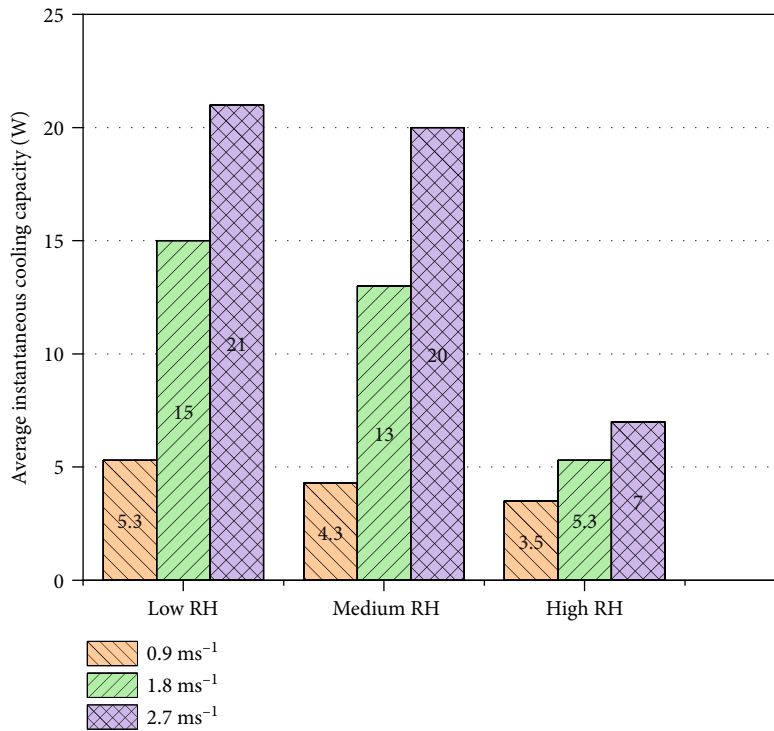
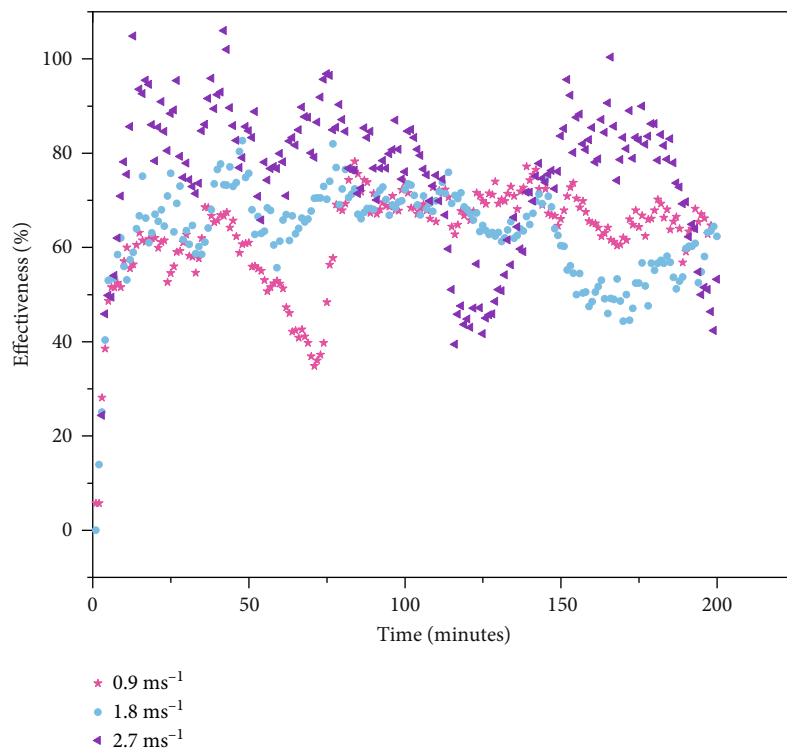


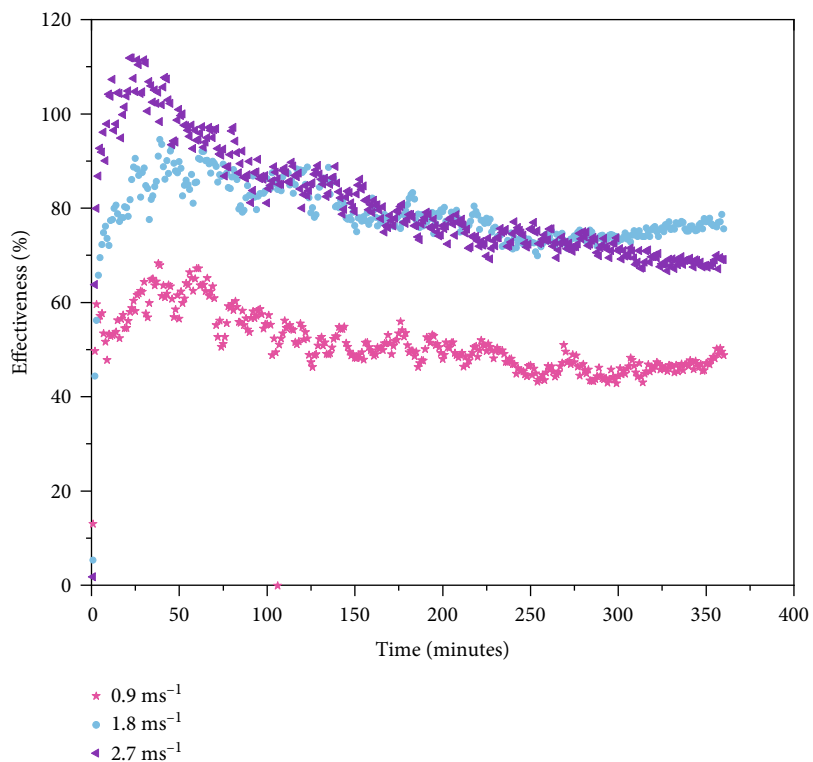
FIGURE 12: Average instantaneous cooling capacity of the air cooler at three different velocities under three different RH conditions.

4.3. *Effectiveness.* Figure 13 shows the effectiveness calculated using Equation (2) for three different velocities under three different RH conditions. It is noticed from Figure 8(a) that

for all velocities, the system is very effective for 60 minutes. After that, there are fluctuations which are mainly due to the change in ambient conditions. In Figures 8(b) and 8(c), it is

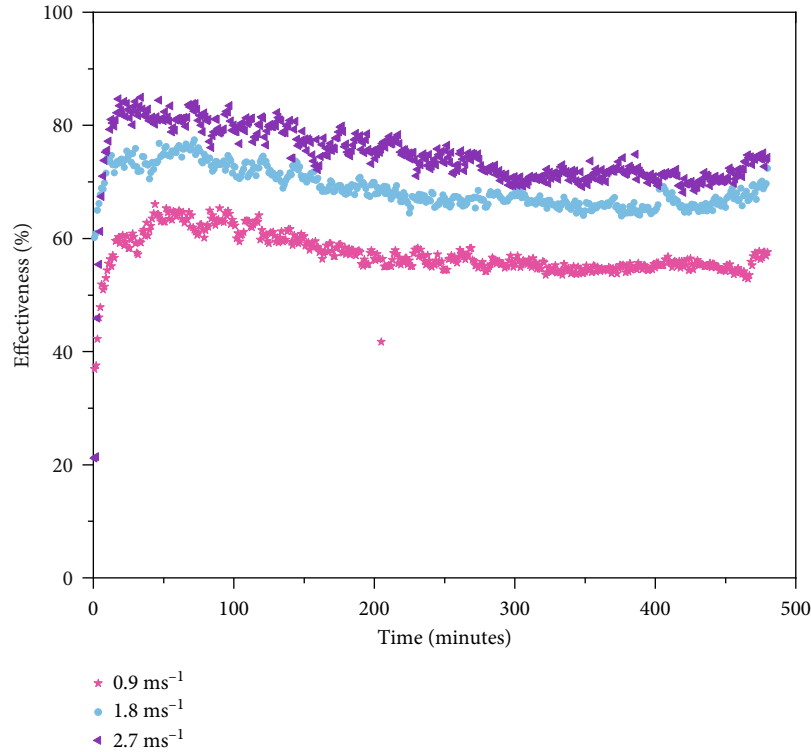


(a) High RH



(b) Medium RH

FIGURE 13: Continued.



(c) Low RH

FIGURE 13: Effectiveness of the air cooler at three different velocities under three different RH conditions.

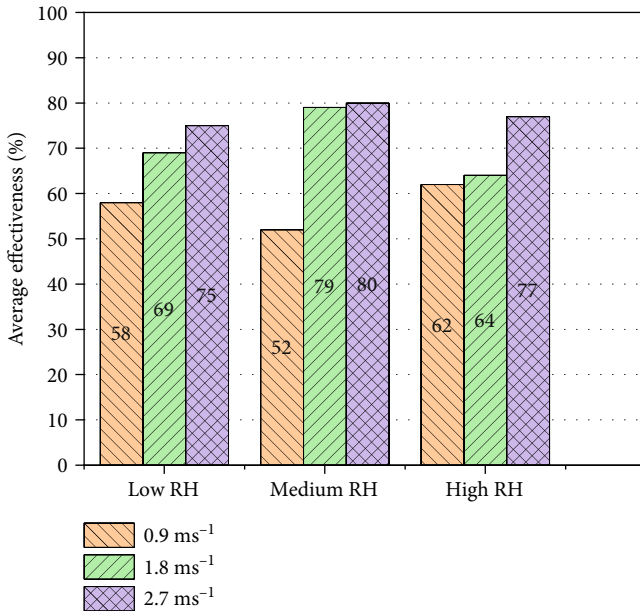


FIGURE 14: Average effectiveness of the air cooler at three different velocities under three different RH conditions.

found that higher average effectiveness was achieved when the velocities of air were 2.7 ms⁻¹ and 1.8 ms⁻¹. The system’s effectiveness was less at 0.9 ms⁻¹ compared to other velocities. It is further observed that the effectiveness was maintained until the end of the experiment, which is mainly due to the water stored in the vermicompost to attain sustainable cooling.

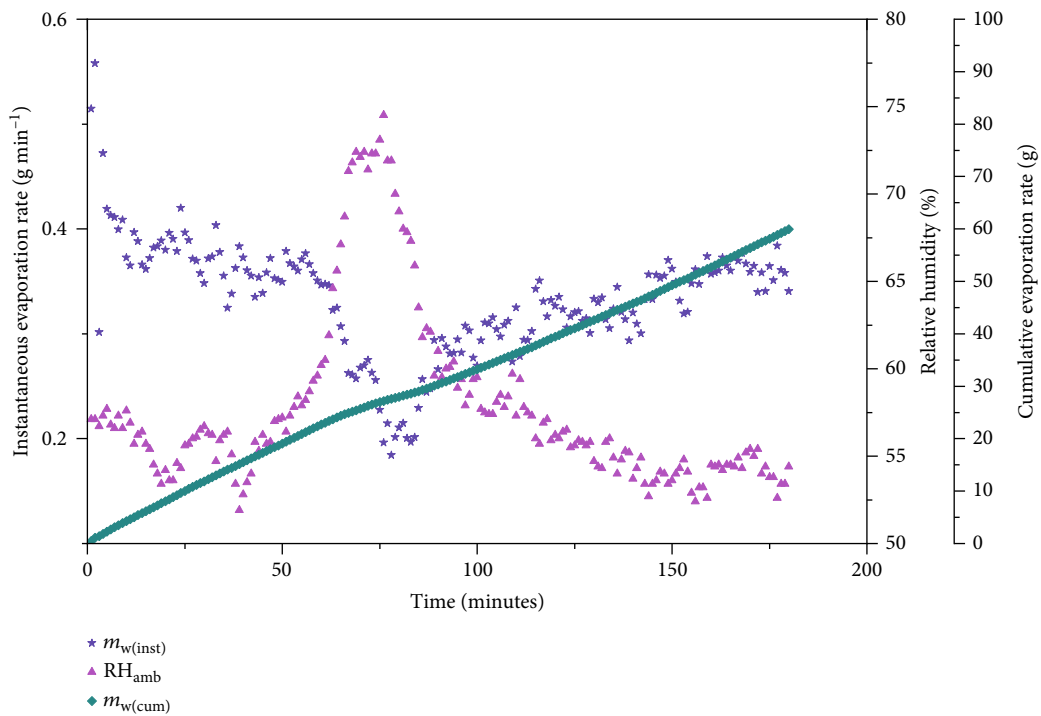
Figure 14 shows the average effectiveness of the vermicompost-based evaporative cooling system tested during three different RH conditions operated at three different velocities. It is clear from the figure that effectiveness is above 75% when the system is operated at high velocity during all RH conditions. It is also understood that the ambient temperature and relative humidity influences the effectiveness of the vermicompost-based cooling system.

4.4. Water Evaporation Rate. Figure 15 shows the instantaneous evaporation rate calculated using Equation (3), cumulative evaporation rate, and ambient relative humidity for three different velocities under high RH condition.

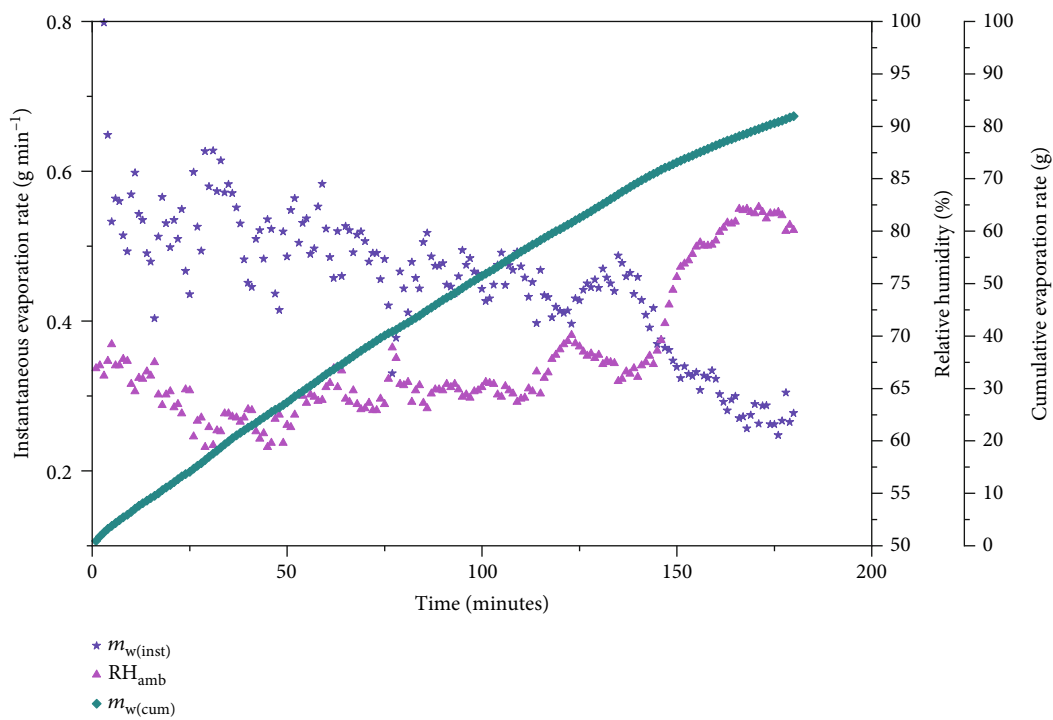
It is observed from the figures that due to the relative humidity, which varies from 60% to 90%, the instantaneous evaporation rate is in the range of 0.2 g min⁻¹ to 0.7 g min⁻¹ at all velocities. However, the average instantaneous evaporation rate is more at 1.8 ms⁻¹ velocity compared to other velocities. The average cumulative evaporation rate is in the range of 60 grams to 80 grams.

It is clear from Figure 16 that the instantaneous evaporation rate increases with velocity, and the average instantaneous evaporation rate is highest for 2.7 ms⁻¹. Its value is in the range of 0.5 g min⁻¹ to 1.0 g min⁻¹. The average cumulative evaporation rate is increased from 200 grams to 400 grams for medium RH conditions.

It is seen from Figure 17 that the instantaneous evaporation rate is more when the air enters dry, i.e., with low relative humidity in the range of 30% to 45%. The cumulative



(a) 0.9 ms^{-1}



(b) 1.8 ms^{-1}

FIGURE 15: Continued.

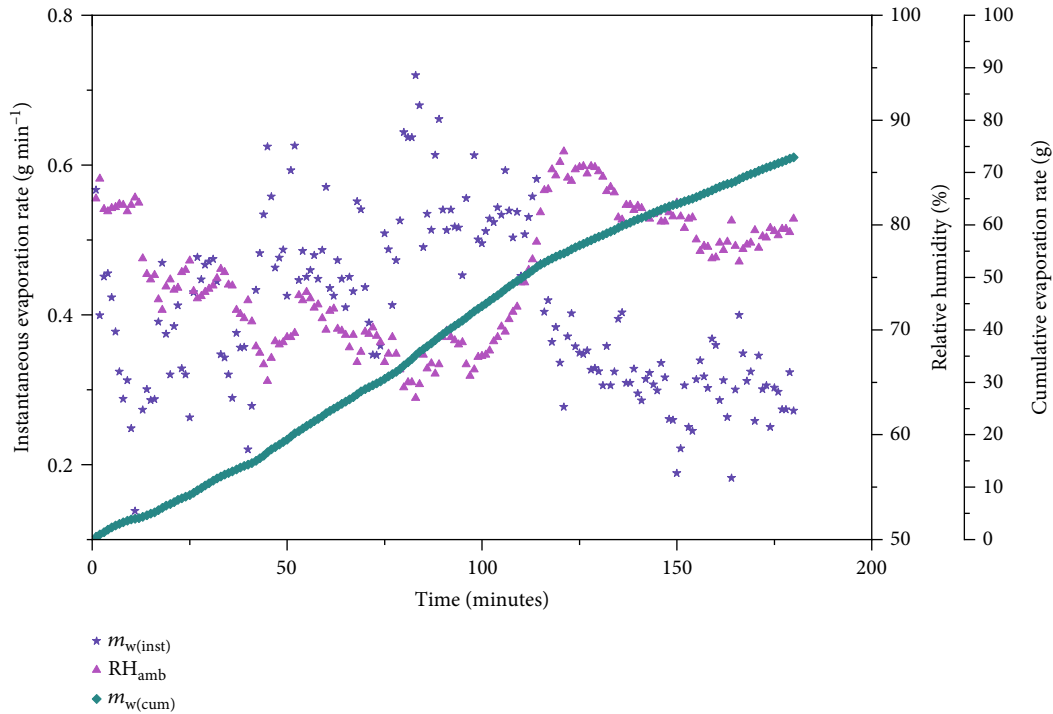
(c) 2.7 ms^{-1}

FIGURE 15: Ambient RH and instantaneous and cumulative evaporation rates of the air cooler at three different velocities under high RH condition.

evaporation rate is also increased, and it is in the range of 250 grams to 550 grams.

Figures 18 and 19 show the average values of instantaneous and cumulative evaporation rates at all velocities for three different RH conditions. It is construed from the figures that instantaneous evaporation and cumulative evaporation rates are inversely proportional to ambient relative humidity and directly proportional to velocity. The highest values are obtained by 1000 grams of vermicompost for low RH condition operated at 2.7 ms^{-1} .

4.5. Economic Analysis. If a pump had been used for supplying the water at the rate of 1 liter per hour, a 0.05 kW pump would have been employed for producing the same cooling effect. The energy consumption for the pump is calculated as follows:

- (i) Power consumption of blower = 0.18 kW
- (ii) Power consumption of blower and pump for conventional evaporative cooling system = 0.23 kW
- (iii) Energy consumed by blower for 8 hours = 1.44 kW – hr
- (iv) Energy consumed by both blower and pump for 8 hours = 1.84 kW – hr
- (v) Energy savings due to the elimination of the pump = 21.7%

Assume a floral shop to be supplied with washed air from a direct evaporative cooler. The flowers are to be kept fresh

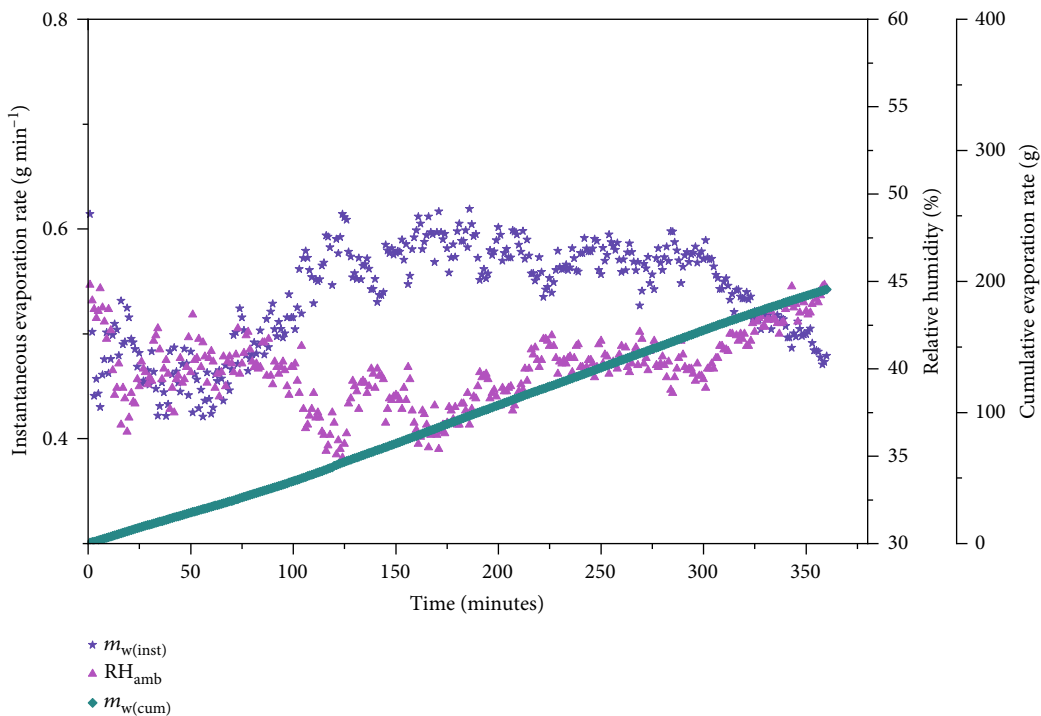
from 5 a.m. to 8 p.m. The applicable monthly tariff for the shop using a conventional evaporative cooler and the present system is given below.

4.5.1. Conventional Evaporative Cooler

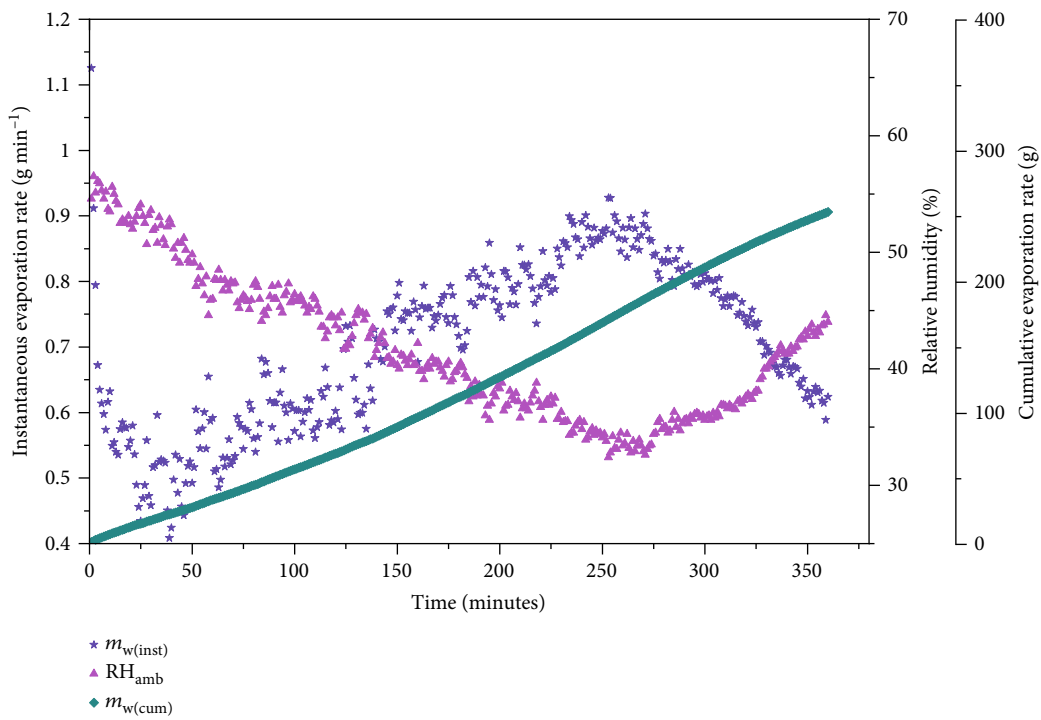
- (i) Energy consumed by the conventional cooler operating for 15 hrs = 3.45 kW – hr
- (ii) Monthly energy consumption = 106.95 kW – hr
- (iii) Energy consumption charge for nondomestic consumers (0 to 100 units) = Rs.5.10/kWh
- (iv) Energy consumption charge for nondomestic consumers (101 to 500 units) = Rs.6.10/kWh
- (v) Fixed charges = Rs.75 per kW per month
- (vi) Total monthly electricity charges for conventional cooler = (Rs.5.10 * 100) + (Rs.6.10 * 6.95) + (Rs.75 * 0.23) = Rs.569.64

4.5.2. Present System

- (i) Energy consumed by the present system operating for 15 hrs = 2.7 kW – hr
- (ii) Monthly energy consumption = 83.7 kW – hr
- (iii) Energy consumption charge for nondomestic consumers (0 to 100 units) = Rs.5.10/kWh
- (iv) Fixed charges = Rs.75 per kW per month



(a) 0.9 ms^{-1}



(b) 1.8 ms^{-1}

FIGURE 16: Continued.

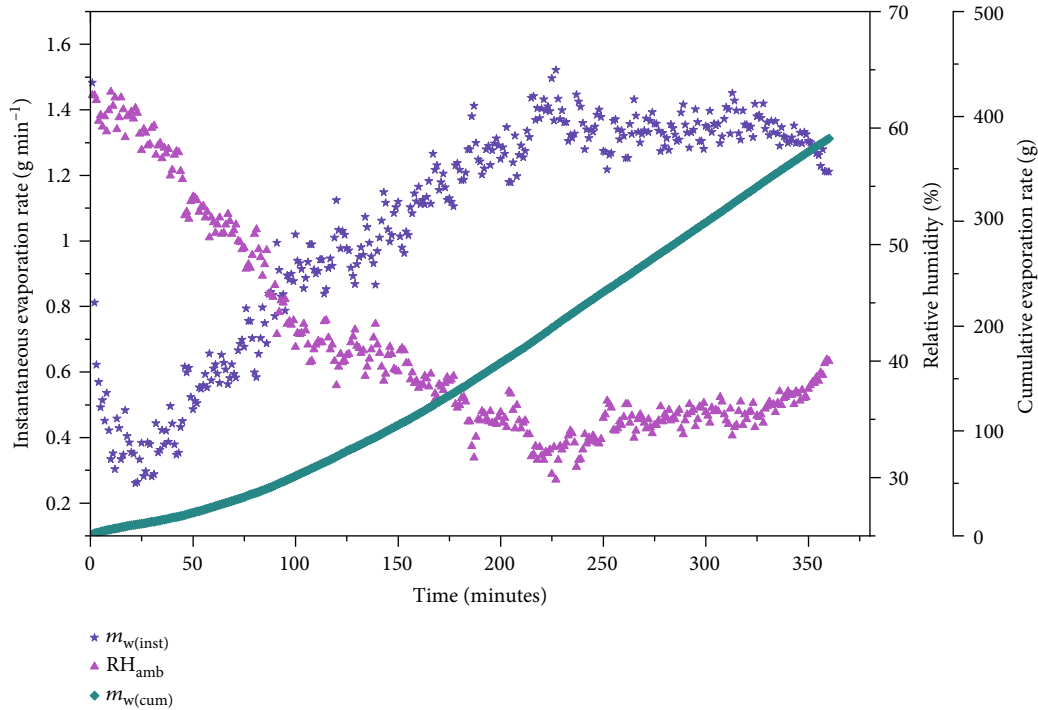
(c) 2.7 ms^{-1}

FIGURE 16: Ambient RH and instantaneous and cumulative evaporation rates of the air cooler at three different velocities under medium RH condition.

(v) Total monthly electricity charges for present system = $(\text{Rs.}5.10 * 83.7) + (\text{Rs.}75 * 0.18) = \text{Rs.}440.37$

(vi) Net monthly savings in electricity charges = Rs. 129.27

(vii) Annual savings in electricity charges = Rs.1551.24

It is understood from the analysis that vermicompost as an energy-efficient material provides thermal comfort by eliminating the pump and issues related to water storage in the sump with energy savings of 21.7% and an annual electricity cost savings of Rs. 1551.24.

4.6. Comparison with Previous Studies. Many researchers had done extensive work in evaporative cooling systems with different pad materials. The results of their investigations are given in Table 4.

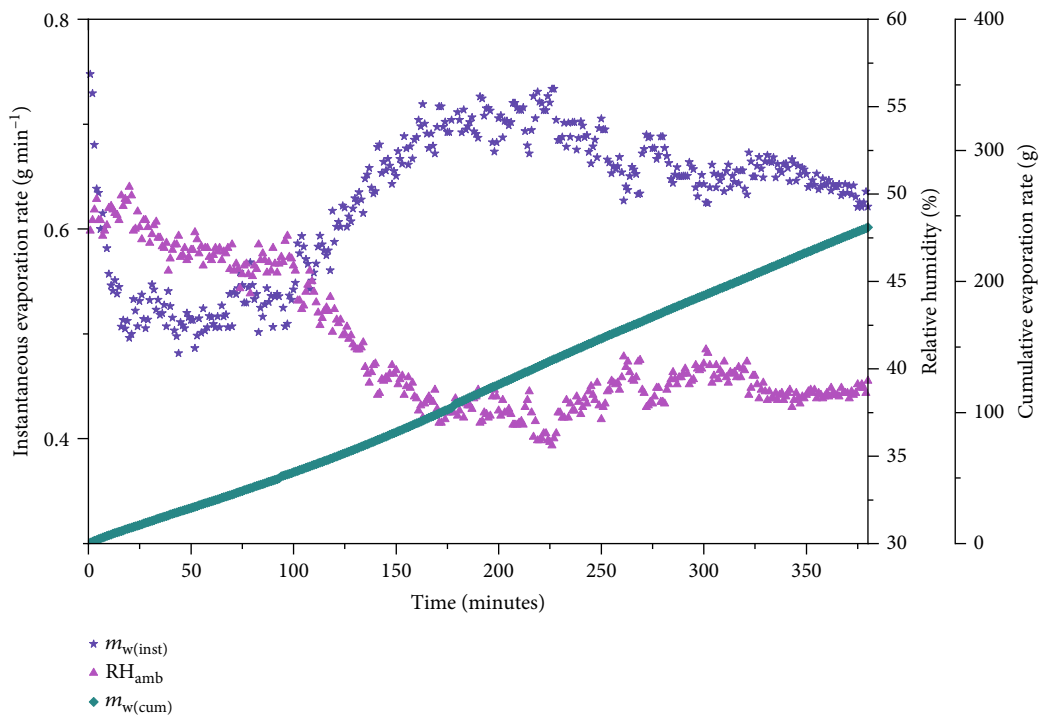
It is observed from the table that the conventional pad-pump system using various pad materials had been used for a hot and dry climate. The effectiveness of the systems varies from 60% to 80%. The highest temperature drop produced by eucalyptus fibre has an effectiveness of 71%. The present vermicompost-based evaporative cooling system produces an average temperature drop of 9.5°C with an average effectiveness of 80% for low RH conditions. Moreover, this system could produce an average temperature drop of 5°C , even during high RH conditions. It is construed that vermicompost has the potential to replace the pad-pump system of the conventional direct evaporative cooling system. Hence, this sys-

tem could be used for cooling applications throughout the year.

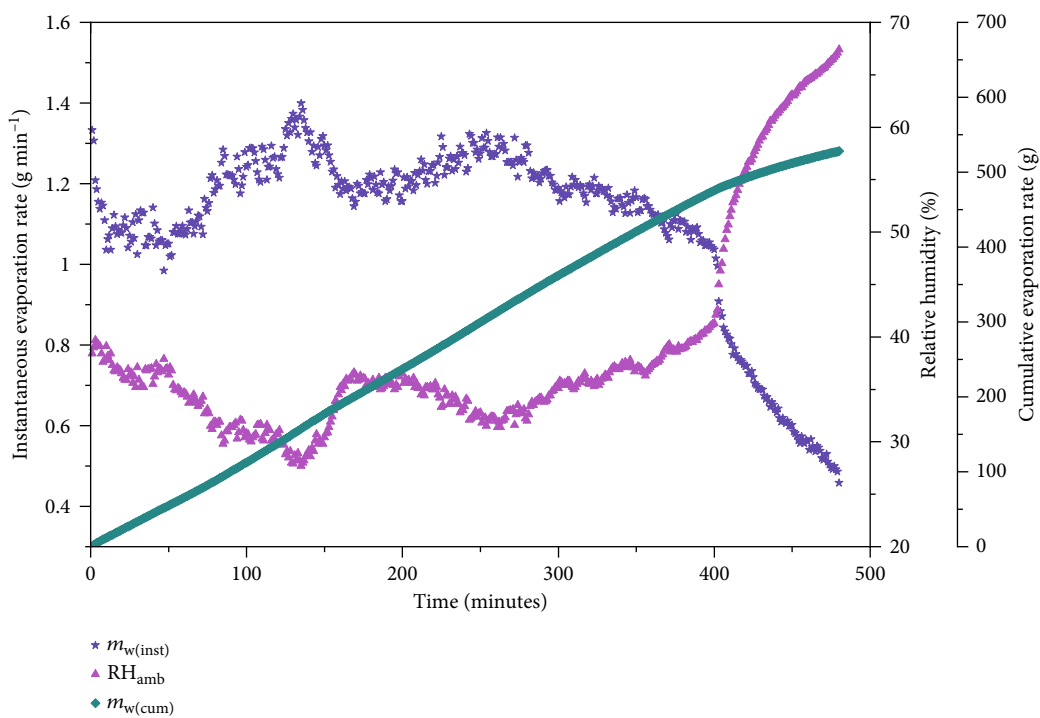
5. Conclusion

The following conclusions are arrived from the present investigation performed on a vermicompost-based evaporative cooling system.

- (i) The vermicompost-based cooling system could produce an average temperature drop of 4°C to 5°C for all velocities up to 150 minutes, as the ambient relative humidity varied from 60% to 75% during high RH condition
- (ii) For medium RH condition, an average temperature drop of 5°C to 8°C and relative humidity of 99% could be achieved with this system based on the operating velocity if the ambient air has a temperature of 30°C to 34°C and relative humidity of 45% to 60%
- (iii) An average temperature drop of 6.5°C to 9.5°C and relative humidity of 99% could be achieved with this system based on the operating velocity when the ambient air has a temperature of 38°C to 42°C and RH of 30% to 45% for low RH condition
- (iv) The vermicompost-based evaporative cooling system performs better at velocities of 1.8 ms^{-1} and 2.7 ms^{-1} during low and medium RH conditions

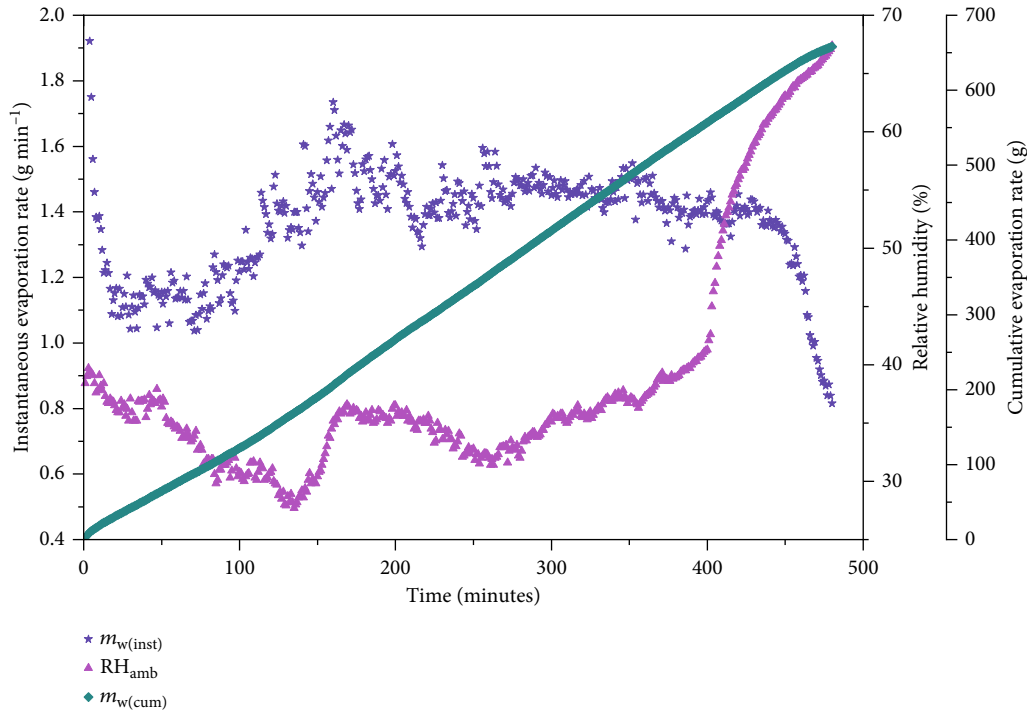


(a) 0.9 ms^{-1}



(b) 1.8 ms^{-1}

FIGURE 17: Continued.



(c) 2.7 ms^{-1}

FIGURE 17: Ambient RH and instantaneous and cumulative evaporation rates of the air cooler at three different velocities under low RH condition.

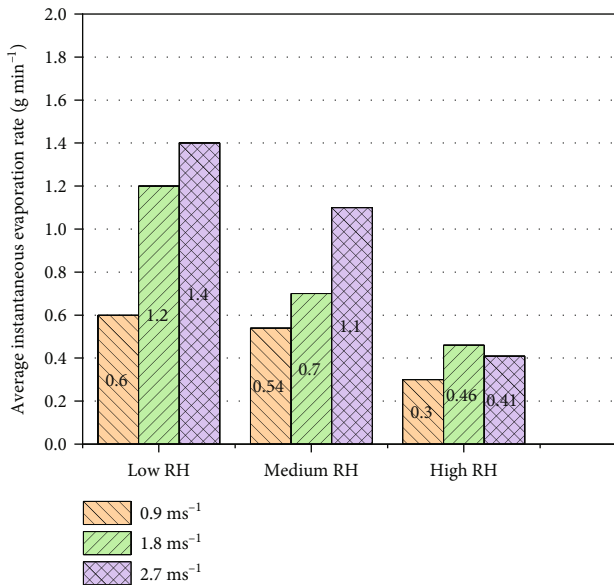


FIGURE 18: Average instantaneous evaporation rate of the air cooler at three different velocities under three different RH conditions.

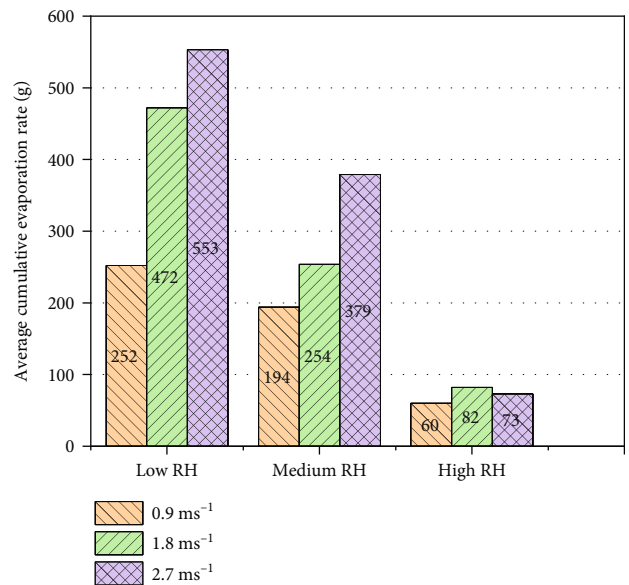


FIGURE 19: Average cumulative evaporation rate of the air cooler at three different velocities under three different RH conditions.

- (v) Ambient relative humidity and operating velocity are the key factors that influence a vermicompost-based evaporative cooling system's performance
- (vi) This system produces the cooling effect by utilizing only the initial water supply and eliminating the water sump system and related health issues. Hence,

the vermicompost-based cooling system can produce higher cooling rates and sustained cooling at higher velocities and low RH conditions

- (vii) Effectiveness is above 75% when the system is operated at high velocity during all RH conditions

TABLE 4: Research outcomes of different pad materials in evaporative cooling.

Authors	Material	Country	Temperature drop (°C)	Effectiveness (%)	Velocity (ms ⁻¹)
Bishoyi et al. [6]	Honeycomb	India	8	75-80	1.5
Al-Sulaiman [7]	Jute	Saudi Arabia	—	62.1	3-4
Doğramacı et al. [8]	Eucalyptus fibre	United Kingdom	11.3	71	0.1-1.2
He and Hoyano [15]	Ceramics	Japan	3-4	50-70	1-2
Katsuki et al. [16]	Ceramics with Onggi clay and bamboo charcoal	Korea	3.6	—	0.4
Soponpongpipat and Kositchaimongkol [22]	Rice husk	Thailand	3.3	60	1
Present work	Vermicompost	India	9.5	80	0.9-2.7

- (viii) Instantaneous evaporation and cumulative evaporation rates are inversely proportional to relative humidity and directly proportional to velocity. The highest values are obtained by 1000 grams of vermicompost for low RH condition operated at 2.7 ms⁻¹
- (ix) It could be used under all operating conditions; however, excellent performance characteristics are observed when the system is operated under low RH conditions. Hence, the vermicompost-based evaporative cooling system could be used in places with hot and dry weather conditions
- (x) The use of a solar dryer for regenerating the vermicompost ensures the prevention of mould growth in the cooling chamber

This energy-efficient cooling technology has the potential to provide a clean and sustainable indoor environment throughout the year in places with hot-dry weather conditions. This system acts as a water storage medium and thus eradicates the problems of water stagnation. The elimination of the pump increases the energy savings of the system by 21.7% and an annual electricity cost savings of Rs. 1551.24. This system could pave the way for year-round thermal management of building cooling applications in an environmentally friendly manner. The present setup technically demonstrates the lab-scale feasibility of a vermicompost-based evaporative cooling system. When it is proposed to make it a user-friendly commercial setup, new limitations and challenges may arise. The future scope of the work is to test the life cycle of the vermicompost in the repeated charging and discharging cycles for long-term utilization.

Abbreviations

DEC: Direct evaporative cooling
DHT: Digital hygro thermometer
TRHS: Temperature relative humidity sensor
RH: Relative humidity.

Symbols

T_{amb} : Ambient temperature (°C)
 T_{al} : Temperature of air leaving the cooling chamber (°C)

T_{wbt} : Thermodynamic wet-bulb temperature of entering air (°C)
 RH_{amb} : Ambient relative humidity (%)
 RH_{al} : Relative humidity of air leaving the cooling chamber (%)
 \dot{m}_a : Mass flow rate of air (kgs⁻¹)
 c_p : Specific heat capacity of moist air (J kg⁻¹ K⁻¹)
 Q_{ec} : Evaporative cooling capacity (W)
 \dot{m}_{wi} : Instantaneous evaporation rate of water (g min⁻¹)
 \dot{m}_{wc} : Cumulative evaporation rate of water (g).

Greek Symbols

ε : Effectiveness (%)
 ω_1 : Humidity ratio of inlet air (kg_w.kg_{dryair}⁻¹)
 ω_2 : Humidity ratio of leaving air (kg_w.kg_{dryair}⁻¹).

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

References

- [1] "How evaporative cooling works," 2020, <https://www.pinterest.com/pin/328692472785595064/>.
- [2] L. Rong, P. Pedersen, T. L. Jensen, S. Morsing, and G. Zhang, "Dynamic performance of an evaporative cooling pad investigated in a wind tunnel for application in hot and arid climate," *Biosystems Engineering*, vol. 156, pp. 173–182, 2017.
- [3] J. Xu, Y. Li, R. Z. Wang, W. Liu, and P. Zhou, "Experimental performance of evaporative cooling pad systems in greenhouses in humid subtropical climates," *Applied Energy*, vol. 138, pp. 291–301, 2015.
- [4] K. Harby and F. Al-Amri, "An investigation on energy savings of a split air-conditioning using different commercial cooling pad thicknesses and climatic conditions," *Energy*, vol. 182, pp. 321–336, 2019.
- [5] A. K. Dhamneya, S. P. S. Rajput, and A. Singh, "Theoretical performance analysis of window air conditioner combined with evaporative cooling for better indoor thermal comfort

- and energy saving,” *Journal of Building Engineering*, vol. 17, pp. 52–64, 2018.
- [6] D. Bishoyi and K. Sudhakar, “Experimental performance of a direct evaporative cooler in composite climate of India,” *Energy and Buildings*, vol. 153, pp. 190–200, 2017.
- [7] F. Al-Sulaiman, “Evaluation of the performance of local fibers in evaporative cooling,” *Energy Conversion and Management*, vol. 43, no. 16, pp. 2267–2273, 2002.
- [8] P. Abohorlu Doğramacı, S. Riffat, G. Gan, and D. Aydın, “Experimental study of the potential of eucalyptus fibres for evaporative cooling,” *Renewable Energy*, vol. 131, pp. 250–260, 2019.
- [9] J. K. Jain and D. A. Hindoliya, “Experimental performance of new evaporative cooling pad materials,” *Sustainable Cities and Society*, vol. 1, no. 4, pp. 252–256, 2011.
- [10] P. M. Cuce and S. Riffat, “A state of the art review of evaporative cooling systems for building applications,” *Renewable and Sustainable Energy Reviews*, vol. 54, pp. 1240–1249, 2016.
- [11] B. Costelloe and D. Finn, “Indirect evaporative cooling potential in air-water systems in temperate climates,” *Energy and Buildings*, vol. 35, no. 6, pp. 573–591, 2003.
- [12] G. Heidarinejad, M. Bozorgmehr, S. Delfani, and J. Esmaeliani, “Experimental investigation of two-stage indirect/direct evaporative cooling system in various climatic conditions,” *Building and Environment*, vol. 44, no. 10, pp. 2073–2079, 2009.
- [13] E. Ibrahim, L. Shao, and S. B. Riffat, “Performance of porous ceramic evaporators for building cooling application,” *Energy and Buildings*, vol. 35, no. 9, pp. 941–949, 2003.
- [14] E. Hajidavalloo, “Application of evaporative cooling on the condenser of window-air-conditioner,” *Applied Thermal Engineering*, vol. 27, no. 11–12, pp. 1937–1943, 2007.
- [15] J. He and A. Hoyano, “Experimental study of cooling effects of a passive evaporative cooling wall constructed of porous ceramics with high water soaking-up ability,” *Building and Environment*, vol. 45, no. 2, pp. 461–472, 2010.
- [16] H. Katsuki, E. K. Choi, W. J. Lee, U. S. Kim, K. T. Hwang, and W. S. Cho, “Eco-friendly self-cooling system of porous onggi ceramic plate by evaporation of absorbed water,” *Journal of the Korean Ceramic Society*, vol. 55, no. 2, pp. 153–159, 2018.
- [17] J. R. Watt, *Evaporative Air Conditioning Handbook*, Chapman and Hall, New York, 1986.
- [18] C. A. Edwards and I. Burrows, “The potential of earthworms composts as plant growth media,” in *Earthworms in Waste and Environmental Management. Hague 2132*, C. A. Edward and E. F. Neuhauser, Eds., SPB Academic Publishing, 1988.
- [19] “Velluru historical weather,” 2020, <https://www.worldweatheronline.com/velluru-weather-history/tamil-nadu/in.aspx>.
- [20] J. R. Taylor, *An Introduction to Error Analysis*, University Science Books, California, 1982.
- [21] S. K. Wang, *Hand Book of Air Conditioning and Refrigeration*, McGraw-Hill, Second, 2001.
- [22] N. Soponpongpiat and S. Kositchaimongkol, “Recycled high-density polyethylene and rice husk as a wetted pad in evaporative cooling system,” *American Journal of Applied Sciences*, vol. 8, no. 2, pp. 186–191, 2011.