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Experimental analysis on humidification-dehumidification desalination system using different packing materials with baffle plates

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ABSTRACT

The primary objective of the present work is to address the issue of the water scarcity problem facing us globally. This manuscript also attempts to incorporate a Humidification-Dehumidification Desalination Technique (HDHT) using artificial and bio-based packing materials. The thermodynamic analysis of a Humidification-Dehumidification Desalination System (HDHDS) by mathematical and experimental methods is studied in detail. To produce the maximum amount of fresh water, two configurations are developed and analyzed under weather conditions prevailing in South India (INDIA). First, the experiments were carried out with artificial packing material (Polypropylene) with and without baffle plates. Next, the second set of configurations used bio-based packing material (Paddy grass) with and without baffle plates. The present analysis inferred that the volumes of fresh water produced were 0.39, 0.46, and 0.73 kg/h without, and with artificial and bio-based packing materials. The rate of fresh water production increased to 36.30% and 46% for artificial and bio-based materials respectively. There was an increase observed in Gain Output Ratio (GOR) as well in the range of 0.28, 0.40, and 0.65 without, and with artificial, and bio-based packing material. GOR increased up to 30% and 56%, when using artificial and bio-based packing material respectively. The present study reveals that the bio-based packing material is highly advantageous in the production of fresh water and in achieving better GOR.

1. Introduction

The tremendous increase observed in population growth, high amount of pollutants discharged from industries directly into water resources and vanishing fresh water reserves result in the rapid shortage of fresh water. Oceans constitute nearly 97% of world's water out of which only 3% is potable that too, present in the poles. Conventional desalination plants which use techniques such as reverse osmosis, multi-effect flash etc. are not adequate for small scale production of fresh water [1]. Continuous efforts have been put forward to resolve these problems by leveraging modern technologies. Researchers are attempting to find novel methods and technologies to produce fresh potable water. It is a major challenge for the scientific community to find a reliable, consistent, and cost-effective technique for clean water production. Among the available techniques, saltwater desalination is considered to be a suitable and optimal technique due to its simplicity and cost-effective nature. Solar-based desalination technology [14,15] i.e., multi-effect desalination is widely adopted these days, thanks to its independent external power operations. However, this technology has few drawbacks such as low gain output ratio and requirement for huge collection area. In potable water generation, several nations are dependent on desalination plants that can meet their daily water requirements. A number of nations started providing attention towards water purification technologies such as desalination, to overcome the shortage of fresh water. To be specific, purification of water using desalination remains the key source of water in dry countries in the Middle East, waterless-isolated zones and few islands. These nations understood the potentials of desalination technique in harvesting potable water. 50% of entire Earth's desalination capacity is located in Middle East, Persian Gulf and Northern African counties. Saudi Arabia tops the world with largest desalination capacity in the world. Nearly 15,906 [2] desalination plants are functioning across the globe, producing 95.37 million m^3/day across 177 nations and territories.

Solar still is one of the simplest ways to produce fresh water and it has been utilized for a long-known time. In spite of all the circumstances and best-functioning performance, the capacity of producing potable water using solar still is approximately 5 l/m^2 per day [3]. Humidification Dehumidification (HDH) desalination method is considered as an

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improved form of solar stills. It can be applied in small-scale production of fresh water in remote areas using waste heat source or solar energy [4]. Affordable potable water remains a big challenge for large production desalination plants, especially in remote parts of the world. In this view, Humidification-Dehumidification (HDH) process is considered as a promising desalination technique to produce potable water in remote areas [5]. This is because the process can operate under atmospheric pressure with the help of low grade renewable energy. HDH mimics the process of natural water cycle in which the air gets humidified initially and then condensed later to produce fresh water. HDH desalination unit consist of two major components such as humidifier and dehumidifier; these components can be operated by different heat sources. Heat source may be fueled by solar energy, geothermal energy, or unwanted heat from process plants [6].

1.1. Literature review

There are research investigations being carried out on renewable energy sources across the globe due to increase in awareness about global climate change. In a study conducted earlier [7], the authors experimented on HDH unit using a special type of solar collector that heats both air and water simultaneously. The researchers inserted semicircular tubulars in air flow path to analyze the performance of system and found an increase in air flow, water and air temperature whereas hot and cold water increased the production of fresh water. Dai et al. [8] studied a system in which solar energy is used to run humidification dehumidification plant containing packed bed humidifier with cross flow arrangement. They established that the performance of a plant can be decided as a function of flow rate of seawater and air and the temperature of inlet water to humidifier. Desalination plant, run with solar energy, is generally monitored through few parameters such as air temperature, moisture content, and collector surface area. The performance of such desalination plants is primarily dependent on specific location, where the climatic conditions are favorable for HDH processes [17]. Orfi et al. [9] conducted a study in which air HDH unit was operated using solar energy. Theoretical analysis including energy and mass balancing was carried out for HDH unit. The authors concluded that the best performance could be achieved by constant tuning of the sea water and air mass flow rate.

Siddiqui et al. [10] carried out an experimental analysis on HDH desalination system which consists of humidifier, heat source and condenser. The experimental work was divided in to two sets. The first set had no solar heat source for heating air and contained two electric water heat sources. The next set contained solar heat source to heat the air and the setup had one water heat source. The study inferred that few performance parameters such as fresh water yield and gain output ratio were better in the second set compared to first set. Further, cost per liter production in second set was low compared to first set of the experiment. Chiranjeevi et al. [11] carried out an experiment and simulation work, on two-stage HDH desalination unit, and utilized an A/C plant. The results showed that about 100 ml of fresh water was produced with the supply of 1 m^3 of air. Also, the fresh water yield got increased in the second stage. Kabeel and El-Said [12] carried out an experimental work on HDH unit integrated with solar energy inserting baffles in the cooler. They found that the unit performance got improved with increasing water temperature and mass flow rate of air. A new approach with heat recovery and solar heat pump was experimentally carried out by Xu et al. [13]. Furthermore, two packing materials i.e., honey comb and polyhedron empty balls, present in the humidifier, were compared. In literature [14], a numerical investigation was carried out using HDH desalination driven by heat pump. The study included theoretical and mathematical model using thermodynamic equations for every unit of the system and the experimental results were validated. Yin Zhang et al. [14] conducted an experimental study upon HDH desalination system with heat pump unit. The study found that the proposed heat pump in the system transferred the heat to saline water and produced a maximum yield of 22.26 kg/h. Kun li et al. [15] investigated a novel household water purification system using heat pump based on HDH technique. They compared this technology with available RO technique.

Selection of packing material for humidifier is one of the additional approaches to increase the effectiveness of the system. Several kinds of humidifiers are used for different types of experimentation procedures such as bubble columns [16], packed bed towers [17], and spray towers [18]. Narayan et al. [19] conducted an experiment on packed bed towers to analyze the effect of water-air interaction duration. It was inferred that high efficiency can be achieved in case of long contact time. Generally, there are two extensive packing methods i.e., splash and film type packings are applicable between which film type packing is the preferred one due to its better thermal performance.

Gharagheizi and Reza et al. [20] carried out an experimental study on two different types of film packing such as vertical corrugated packing and horizontal corrugate packing. The obtained results inferred that the performance of humidifier got influenced by kind and orientation of the packing. Also, the performance of humidifier got reduced when liquid-to-air ratio was increased. The results concluded that the humidifier with vertical corrugated packing has high efficiency compared to horizontal corrugated packing. Kabeel and El-said [21] carried out an experiment on HDH in combination with one-stage flashing evaporation system. The circular shaped polyvinyl chloride packing material, with a dimension of 0.4 m height and 0.8 m diameter, was used in the humidifier. The flow of water got heavily affected compared to that of air flow rate on the effectiveness of humidifier. Al-Enezi et al. [22] analyzed a HDH system which included a packing material made up of plastic in the humidifier, a heat source to heat the water up to 45 °C, an air heater and a condenser. The study examined the effect of entry water temperature, high mass rate of air, and low cooling water temperature and inferred that these characteristics play a highly significant role in fresh water production.

A number of researchers utilized inserts to increase the influence of air flow in air heating source of HDH system. Thianpong et al. [23] carried out an experiment on straight and twisted tapes in the passage of air movement. The heat transfer got increased due to the above inserts. Eimsa-ard et al. [24] studied short length and full length-twisted tapes to investigate air flow features. The research found that short length produced excellent turbulence at inlet flow and increased heat transfer. Different research investigations analyzed the performance of HDH processes at various geographical locations such as Saudi Arabia, Egypt, and India. It is a general observation that HDH-based hybrid system increases yield with proper condensation that ultimately reduces the energy consumption. Better performance can be achieved from hybrid desalination plants under hot and humid atmosphere. Fresh water production is primarily dependent on the humidity of air. So, it becomes important to increase the humidity of air by different means such as design modification, geometrical property variation, baffle insertion, etc. One of the best methods of increasing air humidity is passing it through wet porous media in which more interaction time is available to absorb the moisture. The humidity of air can also be increased by spraying saline water at a slightly higher temperature. But the quantity of water sprayed and air volume flow rate also influences the GOR [18].

Various studies have been conducted to increase the heat transfer by introducing inserts at air inlet and dehumidifier of the HDH system. A research gap has been identified i.e., no studies were conducted so far in which baffle plates are inserted in dehumidifier with the introduction of new packing material (paddy grass). Packing materials such as paddy grass and polypropylene materials are also used in humidifiers to increase the moisture carrying capacity in humidifier. The current study made use of two packing materials in humidifier to experimentally examine various parameters on the performance of HDHDS system such as fresh water production and gain output ratio. The results obtained in terms of fresh water productivity were compared with previous studies. Further, bio-based humidifier packing material was also compared with polypropylene packing material and without packing on fresh water production of the system.

2. Materials and methods

2.1. Polypropylene

Polypropylene is a group of polyolefins with partial crystalline and non-polar characteristics. It is slightly harder and is heat resistant than polyethylene [25]. Fig. 1 shows the actual picture of polypropylene packing material.

It is a white and mechanically-rough product with better chemical resistance. The density of polypropylene is 0.855 g/cm^3 with a melting temperature of 130 to 171 °C.

2.2. Paddy grass

Paddy grass, an agricultural by-product, is nothing but the dry stalks of paddy plants after harvesting the grains. Paddy grass is almost half the yield of paddies like crops such as barley, oats, rice, and wheat. This material is widely available, cost-effective, user-friendly and non-polluting in nature. Fig. 2 shows the actual picture of paddy grass packing material. One can pack paddy grass in two ways while in the first way, the paddy grass is kept horizontal and in the second one, it is kept vertical. The current study used 1600 paddy grass with each having a diameter of 0.005 m and a length of 0.4 m. The packing density of paddy grass was measured to be 157.07 m^2/m^3 with surface area of 10.05 m^2 (Fig. 3).

2.3. Methods

The present study is carried out by two methods i.e., analytical and experimental analyses to evaluate humidification and dehumidification processes. Thermal performance is evaluated by solving continuity, mass balance, and energy equations for both humidifier and dehumidifier. For same specifications, the experimental setup was developed. The results were obtained through analytical and experimental procedures, compared and validated with previously published results.

3. Experimental details

The experimental setup includes binary units such as humidification and dehumidification units. Humidification unit consists of different accessories like water circulating pumps, water sprayers, air blower, and air heater. Dehumidification unit consists of a bunch of coiled copper tubes and baffle plates to produce cooling effect and condense the air moisture. Hot and dry air that pass-through humidifier ducts interacts with sprayed water, absorbs it and reduces the air temperature. This further increases the moisture content of air. Warm moist air is sent to dehumidifier unit which is an indirect contact type, copper-coiled heat exchanger where warm, moist air and chilled water come in contact with a copper tube. Finally, warm humid air is converted into water droplets at the outer surface of dehumidifier and fresh water is collected.

3.1. Working procedure

To initiate the humidification process, atmospheric air is first introduced into air chamber, which is heated using a heat source (location 1: to measure the inlet temperature and humidity of the inlet air). This heating process reduces the humidity of air and increases the moisture absorption capacity [26]. Then the hot air is passed through a lower portion of humidifier. A continuously-circulating water is heated with the help of a second heat source to increase the temperature of water. This preheated water is then sprayed with the help of a water sprayer mounted on the top surface of humidifier (location 4: to measure the inlet temperature and humidity of the inlet hot water). Preheated water is then sprayed using two water sprayers to increase the surface area for water-air contact. The sprayed hot water droplets interact with dry air; through this mechanism, the air absorbs the moisture and gets humidified [27]. The unabsorbed excess water is then collected in water storage tank, placed at the base of humidifier unit (location 6: to measure the outlet temperature of the water). The same water is recirculated using a water pump. Humid air (location 2: to measure the temperature and humidity of the outlet air) is circulated through dehumidifier unit which has a copper tube in the form of a coil through which cooling water (location 7 and 8: to measure the inlet and outlet cold water temperature) flows and condenses the humid air. The condensed water droplets are collected using fresh water collector, placed at the bottom of dehumidifier unit; after losing its moisture content, the dry air (location 3: to measure the dry air temperature) is let out to atmosphere.

Air flow rate and water flow rate are measured by anemometer and rotameters respectively. The fresh water collected is quantified using one liter capacity-water collector placed below the dehumidifier. Psychrometers are located at three different locations such as inlet and exit of the humidifier and at the exit of dehumidifier as shown in Fig. 4.

3.2. Experimental setup components

(a) *Heat source*: Two different heat sources were used in this experimental work i.e., one for heating air and another for heating water. A 500 W capacity heater was used to heat the air, while a 10 kW capacity heater was used for heating water. The actual pictures of the heat source are shown in Fig. 5(a).

(b) *Humidifier*: The process of adding moisture to dry air is carried out in a hollow square-shaped humidifier. The dimensional specifications of the humidifier were 0.4 × 0.4 m cross-section and height of 1 m made up of mild steel material. Air entrance and exit channels are provided at bottom and top portions respectively. The actual pictures of the humidifier are shown in Fig. 5 (c).

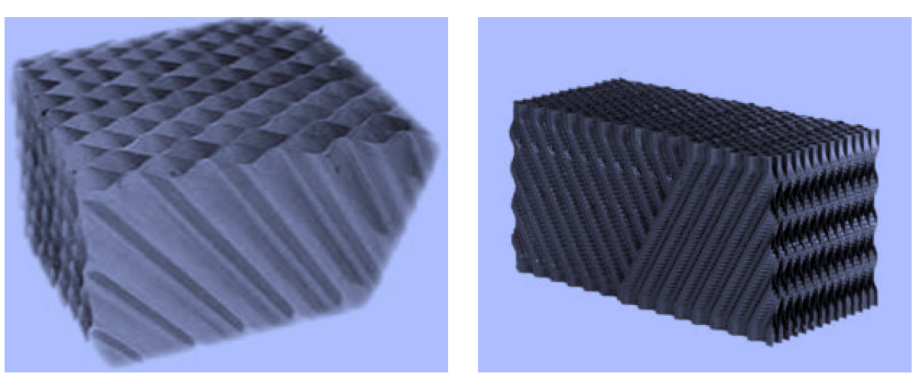


Fig. 1. Actual picture of polypropylene packing material.

Fig. 2. Actual picture of paddy grass packing material.

Fig. 3. Picture of the paddy grass packing material in the humidifier.

(c) *Dehumidifier*: Dehumidifier is modeled as a V-shaped hollow channel with different baffles attached inside the channel. The material used for developing dehumidifier was mild steel with a thickness of 1 mm. The cross-sectional specifications were 0.2 × 0.2 m with 0.8 m length whereas the copper coils and baffle plates were attached along this length. The actual pictures of the dehumidifier are shown in Fig. 5(d).

(d) *Copper coils*: To condensate the moisture content present in humidified air, a copper coil is inserted into dehumidifier. Through this copper coil, cooling water is circulated to reduce the temperature of humid air. The dimensional specifications of the copper coil were outer diameter 100 mm, inner diameter 90 mm and a total length of 4.4 m with total outside surface area of 0.124 m^2. The actual pictures of the copper coil are shown in Fig. 5(e).

(e) *Baffle plates*: Baffle plates are welded inside the dehumidifier channel to increase the condensation process. The technical specifications of the baffles used were 3 mm thick and 0.15

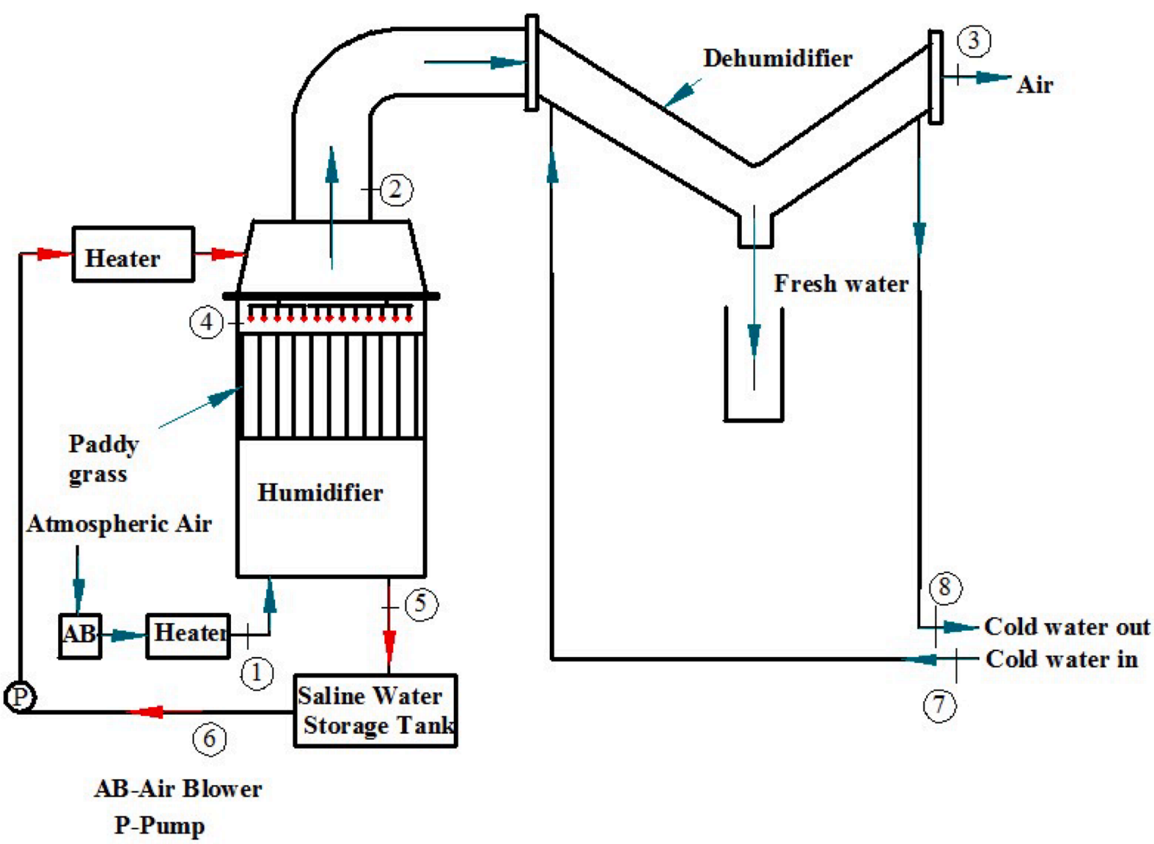


Fig. 4. Block diagram of the humidification dehumidification unit.

(a) The heat source for water
(b) The heat source for air
(c) Humidifier
(d) Dehumidifier
(e) Copper coils
(f) Baffle plates
(g) Water sprayer
(h) Air Blower

Fig. 5. Actual pictures of the experimental setup components.

length. Six baffle plates were welded inside the channel with a gap of 0.16 m. The actual pictures of the baffles used are shown in Fig. 5(f).

(f) *Water sprayer*: In order to increase the area of contact between dry air and the water, hot water is sprayed using two water sprayers mounted at the top of humidifier. Each sprayer consisted of 36 ports with 0.8 cm distance, which breaks the liquid flow into dispersed droplets. The actual pictures of water sprayers are shown in Fig. 5(g).

(g) *Saline water storage tank*: In order to supply the saline water continuously to humidifier, a saline water storage tank of 50-liter capacity was used in this research.

(h) *Air Blower*: Atmospheric air is sucked through air chamber, heated with the help of a heat source and further sent to blower.

The air blower capacity was 500 m^3/hr with inlet and outlet diameters of 7.5 and 8 cm respectively. The speed was 1000 rpm and dry air was supplied up to 20–50 m to humidifier. The actual pictures of the air blower are shown in Fig. 5(h).

(i) *Potable water collector*: One-liter capacity measuring jar is placed below the dehumidifier unit. Through this water collecting jar, the amount of fresh potable water collected at different time instances can be analyzed.

(j) *Thermocouples*: To observe the temperature at different positions, eight thermocouples were installed. The thermocouples used were of K-type thermocouples with specifications of 3 mm diameter, 2 m cable length and working range of −200 to 1200 °C with an accuracy of ± 0.15 °C and uncertainty of 2%.

(k) *Psychrometer*: To analyze the intensity of humidification of dry air-dry bulb and wet bulb, the temperature is measured. Three psychrometers were used at inlet of humidifier and outlets of both humidifier and dehumidifier. By measuring these dry bulb and wet bulb temperatures, the humidity of air can be calculated using psychrometric chart at atmospheric pressure.

3.3. Performance analysis of humidifier and dehumidifier

The thermal performance of humidifier unit is evaluated using the following equations since the humidifier operation is based on heating process, continuity, mass, and energy balance equations [21].

(i) Steady-state energy equation and mass balance for humidifier unit

$$\dot{m}_{sw}h_s - \dot{m}_{drain}h_{drain} = \dot{m}_a(H_{h,i,a} - H_{h,o,a}) \quad (1)$$

$$\dot{m}_a w_1 + \dot{m}_{sw} = \dot{m}_a w_2 + \dot{m}_{drain} \quad (2)$$

where $\dot{m}_{sw}$,$\dot{m}_{drain}$ and $\dot{m}_a$ are mass flow rates of saline water, drain water and mass flow rate respectively whereas h_{drain}, h_s and $(H_{h,i,a} - H_{h,o,a})$ are enthalpies of saline water and air enthalpy difference respectively.

The mass transfer in humidifier can be written as follows [22]

$$\frac{\dot{m}_a}{\dot{m}_{sw}}(H_{h,i,a} - H_{h,o,a}) = \frac{kav}{\dot{m}_{sw}}\left[\frac{(H_{h,i,w} - H_{h,o,a}) - (H_{h,o,w} - H_{h,i,a})}{ln\frac{(H_{h,i,w} - H_{h,o,a})}{(H_{h,o,w} - H_{h,i,a})}}\right] \quad (3)$$

Where: k is the overall mass transfer coefficient of water in air (kg/m^2s), a is the specific mass transfer area (m2/m^3), and V is the packing volume (m^3).

Thermal performance of humidifier is expressed using the following equation and is defined as the ratio of change in humidity at outlet and inlet of the humidifier to the change of saturated outlet air as stated in [28]

$$\eta_h = \left[\frac{w_{h,o,a} - w_{h,i,a}}{w_{3s,a} - w_{h,o,a}}\right] \quad (4)$$

(ii) Steady-state energy equation and mass balance for dehumidifier unit

$$\dot{m}_{clw}(h_{clw,out} - h_{clw,in}) = \dot{m}_a(H_{h,i,a} - H_{h,o,a}) - \dot{m}_{cond}h_{cond} \quad (5)$$

$$\dot{m}_a H_{h,i,a} = \dot{m}_a H_{h,o,a} + \dot{m}_{cond} \quad (6)$$

where;$\dot{m}_{clw}$,$\dot{m}_{cond}$ and $\dot{m}_a$ are the mass flow rates of cold water, condensed water, and air respectively. $h_{clw,out}$,$h_{clw,in}$ and $(H_{h,i,a} - H_{h,o,a})$ are enthalpy of cold-water outlet, cold water inlet and air enthalpy difference respectively.

(iii) Gain Output Ratio (GOR)

The potential Gain Output Ratio (GOR) of humidification dehumidification unit is calculated as follows.

$$GOR = \frac{\sum(h_{fg}m_{freshwater})}{\sum(Q_{Totalheatinput})} \quad (7)$$

The dehumidifier element in the humidification-dehumidification unit is a fin-tube kind heat exchanger where in the interaction of hot humid air and feed water takes place through the gap between fins and tube. The sensible and latent heat transfer occur during dehumidification process. The hot humid air enters the upper portion of the dehumidifier and exits the other end. To examine the performance of the dehumidification process in the dehumidifier, the Ɛ-NTU [29] procedure is adopted. The effectiveness can be written as

$$\varepsilon = 1 - exp\left\{\frac{NTU^{0.22}}{C_R} - \left[exp\left(-C_R NTU^{0.78}\right) - 1\right]\right\} \quad (8)$$

where

$$\text{NTU} = \frac{UA}{m_a c_{pa}} \quad (9)$$

$$C_R = \frac{m_a c_{pa}}{m_c c_{pc}} \quad (10)$$

and

The total heat resistance (1/UA) is expressed as

$$\frac{1}{UA} = \frac{1}{h_i A_i} + R_{wl} + \frac{1}{\eta_f h_a A_a} \quad (11)$$

where the middle term of the right hand side of the equation R_{wl} is the resistance of the wall and η_f is the efficiency of the fin, Ai is the inner surface area of the copper tube and Aa is the heat exchanger area in the air side. The first and last term of the right hand side of the equation are tube side resistance and air side resistance respectively.

During the experimental work the cold water flow rate is 0.05 kg/s and the corresponding Reynold number is 15,300 which is more than 4000. Therefore, flow is considered to be turbulent. Hence, the convective heat transfer coefficient of the water h_i in the expression (12) can be calculated by,

$$h_i = \left(\frac{K_i}{D_i}\right)\frac{(R_{e_{Di}} - 1000)(F_i/2)P_r}{1.07 + 12.7\sqrt{F_i/2}(P_r{}^{0.7} - 1)} \quad (12)$$

$$F_i = \frac{1}{(1.58lnR_{e_{Di}} - 3.28)^2} \quad (13)$$

The heat transfer coefficient h_a for the air side of the dehumidifier is expressed with:

$$h_a = j\frac{m_a c_{pa}}{P_r^{2/3}} \quad (14)$$

$$j = 0.4R_{edc}^{-0.468+0.04076N_r}\left(\frac{A_o}{A_{po}}\right)^{0.159}N_r{}^{-1.261} \quad (15)$$

where $m_a$the mass flow rate of through fins, Ao is the external surface area of the tubes and Apo is the total heat exchange area respectively.

3.4. Measuring devices and uncertainty analysis

The influencing parameters are closely monitored to attain accurate results. The parameters which may influence the results majorly are airflow rate, hot water spray flow rate, air temperature, and relative humidity. Also, the ambient temperature, water temperatures that enter and exit the heat source and water temperature that enter and leave the dehumidifier and condenser units are measured. The uncertainties in the system are calculated using the following equation [30].

$$Uncertainty = \sqrt{\left[\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \left(\frac{\partial R}{\partial x_3}w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2\right]} \quad (16)$$

where: R = Inputs functions $\{x_1, x_2 \ldots x_n\}$. And $w_1, w_2, \ldots w_n$ refers to the uncertainties of these variables.

The percentage uncertainty was found in the range of 0.202 to 0.543 for overall system and individual component uncertainty was calculated and tabulated above. Table 1 shows the uncertainty observed in different measuring instruments.

3.5. Experimental comparison

The experiment was repeated similar to previous analysis in order to compare the present results. The current study results, with same operating parameters and working conditions, were considered. Both the results were found to be similar in an acceptable range, well matched and considered as accurate for further analysis. In the present study, paddy grass material as a packing material produced the highest rate of fresh water compared to other materials. Table 2 shows the experimental comparison of present results and previous study results for different packing materials. Table 3 shows some of the experimentally measured values.

4. Results and discussion

4.1. Effect of flow rates on fresh water production

Throughout the experiment, it is noticed that the low mass flow rate of air resulted in high fresh water production rate. For 0.01 kg/s airflow rate, the water production was at the maximum. When all the three cases were compared, similar patterns were observed. However, when compared to no-packing material, the water production rate got increased with packing material. Compared to no-packing condition, polypropylene packing produced a slightly higher volume of fresh water [37]. Among these working conditions, paddy grass packing material produced excellent results with respect to maximum yield. An increase in airflow to the humidifier increased the production of fresh water. But beyond 0.01 kg/s, it is observed that the extension got reduced in the yield of potable water. This may be due to the fact that an increase in the flow rate reduces the contact time between air and water. This scenario would've decreased the moisture content carrying at the outlet of humidifier [38]. Fig. 6 shows the variations of fresh water production with (a) mass flow rate of air and (b) mass flow rate of water.

The reason for higher production of fresh water is due to large packing wetting area which increased the contact area between air and water. The water was sprayed through packing materials. The degree of wetting of packing surface influenced the flow rate of air and water. Paddy grass exhibited higher productivity compared to polypropylene packing material. The enhanced interaction of water with the air and greater swirling results in more quantity of water particles with the air and hence augmented fresh water at the outlet of the system.

Table 1
Uncertainties observed in different measuring instruments.

Measuring Instruments	Range	Accuracy	Uncertainty
Thermocouple	−200–1200 °C	± 0.15 °C	2 °C
Humidity sensor	0–100% RH	± 2.0 RH	1.75 RH
Airflow meter	0.02–5 m/s	± 0.1 m/s	1.5 m/s
Water flow meter	0.01–4 m/s	± 0.1 m/s	0.5 m/s
Water collector	0–1000 ml	±10 ml	5.5 ml

4.2. Variation of GOR dimensionless parameter with mass flow ratio

The present experimental analysis was carried out for three different cases i.e., without any packing material, with artificial packing material (Polypropylene), and bio-based material (Paddy grass). The effect of these packing materials on fresh water production rate was analyzed using few parameters such as airflow rate and water flow rate. Fig. 7 shows the effect of mass flow ratio with dimensionless factor [KaV/L] of humidifier. It is observed from the figure that increasing the mass flow ratio decreases the dimensionless parameter. The graph exhibited the same trend alike the study conducted by Farhad G [39] in which same experimental work was carried out. However, the only difference in the present work being the usage of paddy grass material with packing density of 157 m^2/m^3.

4.3. Effect of water and air temperature on fresh water production

Fresh water productivity got increased with humidifier inlet air temperature. There was a linear increase observed in water production with air temperature. This might be attributed to the fact that at higher elevations, the water temperature results in better evaporation of water which increases the moisture ability of the air. The maximum water production was achieved at 40 °C under all three working conditions. Though similar trend was observed, a high rate of production was obtained from paddy grass packing material. The variations of fresh water production, with air and water temperature, are shown in Fig. 8. Compared to inlet air temperature, an increase in water inlet temperature affects the production of fresh water gradually. Maximum productivity was obtained for paddy grass packing material at 70 °C humidifier inlet water temperature. This is because at elevated temperature humidity of air rises. This leads to more quantity of moisture conceded by air and therefore more fresh water production of the system. In addition to that, the reason for higher yield is that paddy grass having better packing density compared to polypropylene. The contour of the paddy grass is closely cylindrical which helps in increase the contact area of the air and water in the packing made of grass and hence better packing density. Polypropylene packing results slightly reduced the rate of water production compared to paddy grass, but it significantly produced higher rate compared to no-packing condition.

4.4. Effect of different operating parameters on Gain Output Ratio (GOR)

Gain Output Ratio is a ratio of latent heat of evaporation to the total heat supplied to desalination unit. GOR is an important performance parameter used in humidification and dehumidification processes. It describes the energy evaluation of desalination plant and all other thermal desalination techniques. The value of GOR should be more to the best possible, because the evaluation of any desalination plant should be performed using this parameter. This can be accomplished either by increasing the fresh water for same amount of total heat supplied or get the same amount of fresh water with less amount of total heat energy. Fig. 9 shows the variations of Grain Output Ratio with mass flow rate of air, air temperature, feed water temperature and mass flow rate of water.

It is observed that an increase in the mass flow rate of air increased the fresh water production up to 0.01 kg/s. Above this threshold, it got decreased due to lack of contact time between water and air inside the humidifiers. The maximum amount of fresh water was produced from paddy grass packing material when compared to polypropylene packing material.

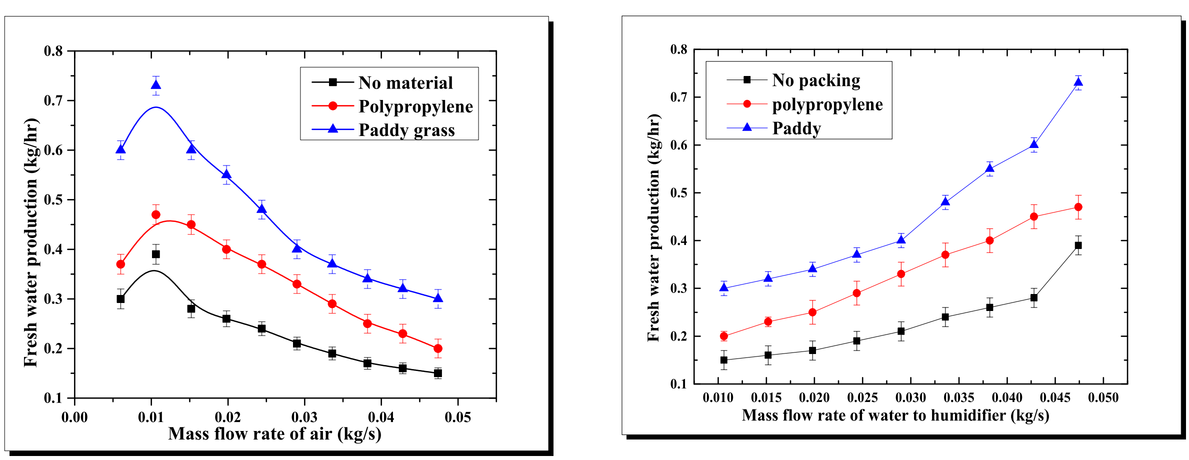
The influence of inlet feed water temperature to humidifier upon Gain Output Ratio is presented in Fig. 9(c). As seen from the graph, similar trend is observed in fresh water production too, in which the gain output ratio got increased particularly after 50 °C.

Table 2
Experimental comparisons of present results and published results for different packing materials.

Mass Flow Rate of Water ($\dot{m}_w$)	Mass Flow Rate of Air ($\dot{m}_a$)	Inlet Temp. (T_1)	Outlet Temp. (T_2)	Packing Materials	Fresh water Production (M_w)		Authors
(kg/s)	(kg/s)	(C)	(C)	*NA*	(kg/hr)	(kg/m^3)	
0.040	0.01	70.0	40.0	Paddy grass	0.735	47	Present study
0.040	0.01	70.0	40.0	Polypropylene	0.465	29	Present study
0.030	0.031	44.0	28.0	Metal	3.200	19	Moumouth et al. [31]
0.002	0.045	36.0	33.0	Cellulose	0.512	40	Nafey et al. [32]
0.012	0.040	68.9	43.4	Cellulose	1.450	0.86	Hermosillo et al. [33]
0.115	0.045	50.0	40.0	Plastic	2.500	17	Yamali et al. [34]
0.530	0.15	49.0	38.73	Aluminum Sheets	15.000	54	Ahmed et al. [35]
0.04	0.01	44.69	53.6	Textile	2.6110	10.87	Zhani et al. [36]

Table 3
Experimental measured data.

$T_{a,i,h}$ (°C)	$T_{a,i,d}$ (°C)	$T_{a,o,d}$ (°C)	$T_{w,i,h}$ (°C)	$T_{w,o,h}$ (°C)	$T_{cw,i,c}$ (°C)	$T_{cw,o,c}$ (°C)	m_{fw} (kg/hr)	m_w (kg/s)	m_a (kg/s)	m_{cw} (kg/s)
26.78	33.78	30.15	35.43	34.01	28.89	30.87	0.312	0.051	0.012	0.045
25.87	34.56	30.57	36.02	34.71	30.01	31.43	0.328	0.051	0.013	0.045
25.14	37.97	31.34	40.12	30.45	30.04	31.84	0.341	0.051	0.012	0.045
26.67	37.78	31.45	40.15	31.89	30.06	31.67	0.345	0.051	0.021	0.045
26.87	38.34	31.98	41.5	30.56	30.12	31.89	0.349	0.051	0.012	0.045
26.78	40.45	32.09	43.76	33.17	30.17	32.04	0.355	0.051	0.017	0.045
25.98	40.23	32.45	43.56	32.19	29.99	32.02	0.356	0.051	0.012	0.045
25.14	40.65	32.34	43.66	32.67	30.13	32.21	0.361	0.051	0.013	0.045
26.67	48.45	34.65	50.11	37.98	30.12	33.98	0.365	0.051	0.012	0.045
26.87	48.56	34.21	50.91	37.65	30.13	33.79	0.368	0.051	0.021	0.045
26.78	48.23	34.67	50.02	36.88	30.12	32.86	0.362	0.051	0.012	0.045
25.42	48.61	34.37	54.33	34.87	28.97	35.08	0.398	0.051	0.021	0.045
25.14	48.22	35.02	54.67	34.12	28.78	34.98	0.391	0.051	0.012	0.045
26.67	49.67	40.87	55.01	33.78	28.98	34.65	0.392	0.051	0.017	0.045
26.87	51.55	41.9	60.78	41.34	27.08	37.32	0.432	0.051	0.012	0.045
26.78	51.62	42.01	60.43	42.22	28.12	37.87	0.453	0.051	0.013	0.045
25.87	51.72	42.45	60.32	43.12	30.12	37.53	0.495	0.051	0.012	0.045
25.14	52.33	41.88	61.76	42.45	30.13	38.21	0.521	0.051	0.021	0.045
26.67	53.89	34.89	65.19	41.91	30.12	39.32	0.589	0.051	0.012	0.045
26.87	53.34	35.12	65.09	41.56	28.97	39.63	0.612	0.051	0.021	0.045
26.78	55.34	40.45	68.45	35.34	29.78	40.31	0.63	0.051	0.012	0.045
25.9	55.71	41.01	69.01	34.45	29.98	40.88	0.719	0.051	0.017	0.045
25.14	56.88	39.99	70.01	34.34	29.76	40.93	0.729	0.051	0.012	0.045



(a) (b)

Fig. 6. Variation of fresh water production with (a) mass flow rate of air and (b) mass flow rate of water.

4.5. Effect of baffle plates on fresh water production

From the literature, it has been observed that non-condensable water vapor results in substantial reduction of condensation heat transfer [40]. The quantity of non-condensable water vapor varies in the range of 40–95%, when moisture is removed from moist air in dehumidifier. In order to improve heat transfer coefficient, some necessary action should be taken. Hence, baffle plates are placed inside the dehumidifier. Firstly, because of the turbulence of the air generated by the baffle plates increases and consequently boundary layer due to condensation is altered

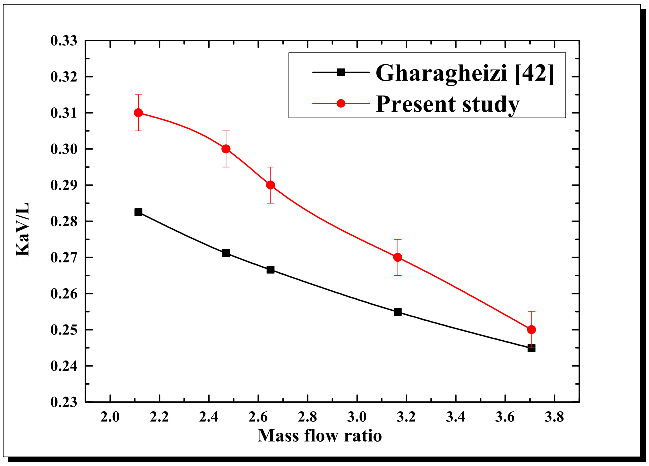


Fig. 7. The variation of dimensionless parameter with the mass flow ratio (ma = 0.01 kg/s,m_{cw} = 0.05 kg/s).

and hence reasonable better condensation heat transfer coefficient is achieved subsequently augmented fresh water from the dehumidifier. Secondly, due to the prolonged time for the humid air on the outer copper tubes results in higher fresh water. It is found from the experiment that the fresh water productivity got increased to 0.785 kg/hr-m^2, when baffle plates were inserted in dehumidifier. The baffled arrangement in dehumidifier increased the productivity upto 60% in comparison with non-baffled dehumidifier (Fig. 10.).

4.6. *Influence of cooling water flow rate to dehumidifier*

Fig. 11 indicates the variations of cooling water on fresh water production. As observed from the figure, the yield got increased with increase in the mass flow rate of cold water. As a result of increasing the flow rate of cold water, the temperature of cold water got decreased. Accordingly, external peripheral temperature of the dehumidifier also got reduced and hence better heat transfer from the hot humid air to the cold water. This helped in reducing the air temperature and hence moisture removal capacity from humid air also got increased. And to end with more condensation of vapor from the moist air, the fresh water production is 0.39, 0.47 and 0.73 kg/h for without, artificial and paddy grass packing material respectively.

4.7. *Influence of mass flow ratio and temperature*

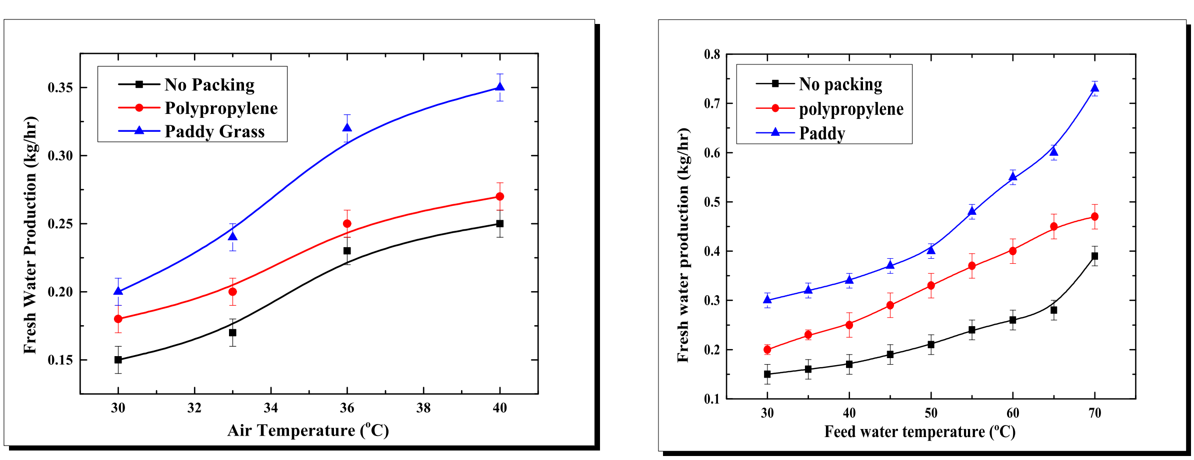
The performance of humidifier is expressed by dimensionless parameter which is identical to what is accepted in case of cooling tower [41]. This parameter is calculated using the Eq. (3). As observed from the Fig. 12(a), the elevating mass flow ratio reduced the dimensionless parameter. Furthermore, the dimensionless parameter got influenced with sea water temperature inlet to humidifier as exhibited in Fig. 12(b). In this figure, the parameter increased with increasing inlet sea water temperature.

Fig. 13 displays the effect of mass flow rate of air and air temperature on humidifier efficiency. It can be observed that there was a decrease in humidifier efficiency with increasing air temperature and mass flow rate. Due to this reason, the moisture carrying capability got increased with increase in temperature. As a result, the air coming out of humidifier was far away from saturation point at a specified moisture transfer. Furthermore, the humidifier efficiency got decreased with increase in mass flow rate of air. This might be attributed to the reduction of interaction time between air and water. As a result, the humidity ratio got decreased and finally, the air got unsaturated at the exit of humidifier.

5. Conclusions

In the present research work, a detailed thermal analysis of humidification and dehumidification systems was conducted with three different cases i.e., with no packing material, artificial packing material, and bio-based packing material together with and without baffle plates for each case. The complete study was carried out following two methods such as analytical calculation and experimental analysis. The effect of different parameters such as inlet water, airflow rate, and inlet temperatures on fresh water production and gain output ratio were investigated. From the present study, the following conclusions are drawn.

- Fresh water production rates, in the current study, were 0.39, 0.46 and 0.73 kg/h for without packing and with artificial and bio-based packing materials respectively.
- The fresh water production rate increased to 17% and 46% for artificial and bio-based materials respectively.
- Gain Output Ratio (GOR) increased in the range of 0.28, 0.4 and 0.65 without packing and with artificial and bio-based packing materials respectively.



(a) (b)

Fig. 8. Variation of fresh water production with (a) Air Temperature and (b) Water temperature.

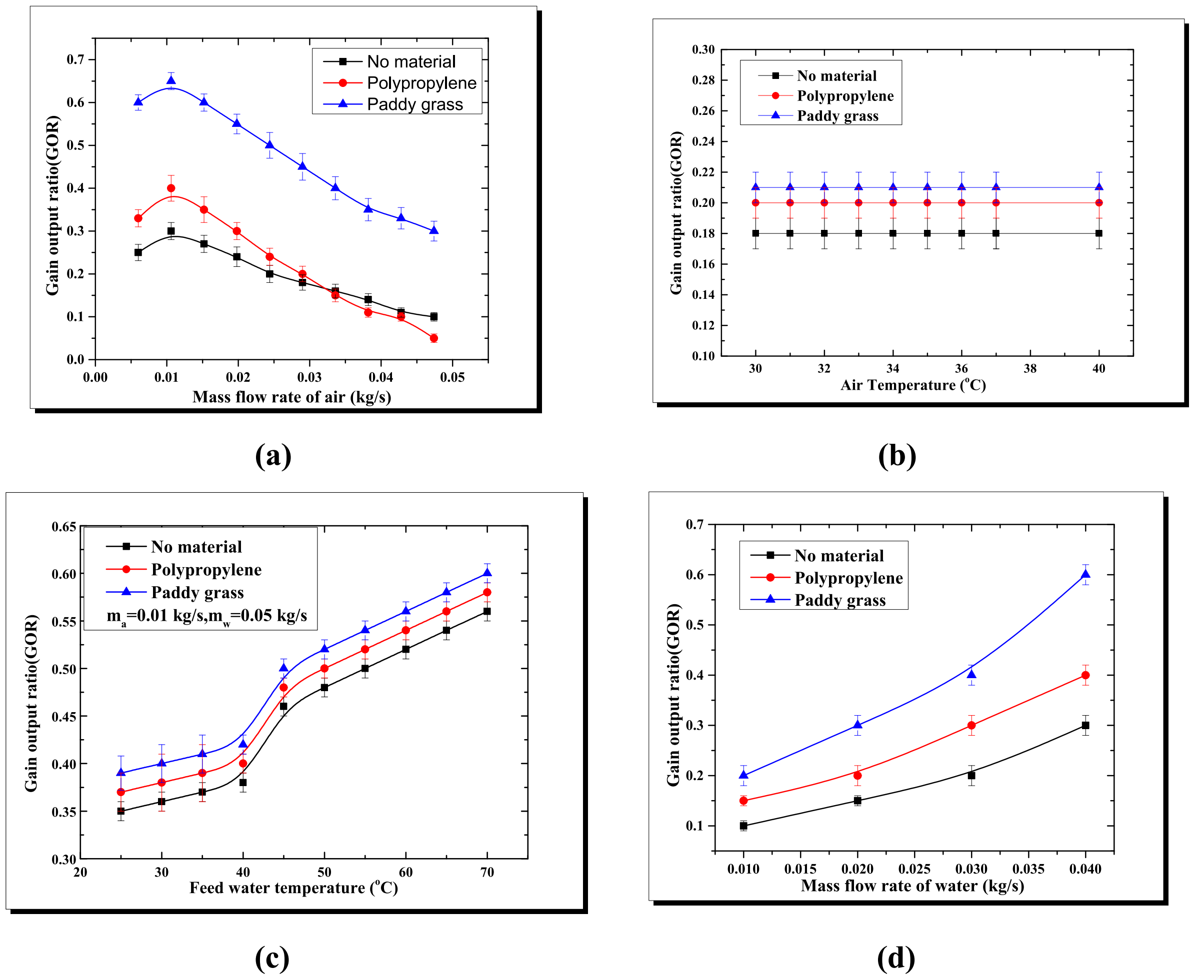


Fig. 9. Variation of GOR with (a) mass flow rate of air (b) air temperature (c) feed water temperature and (d) mass flow rate of water.

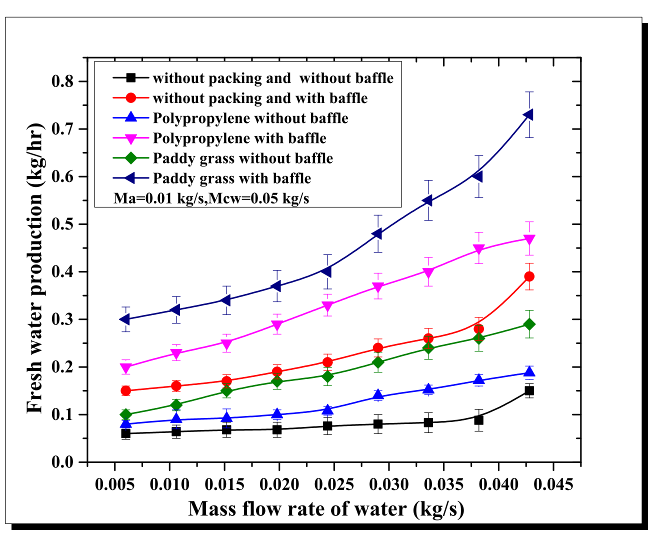


Fig. 10. Effect baffle plates on fresh water production.

- There was an increase observed in GOR percentage i.e., 30% and 56% for artificial and bio-based packing materials respectively.

The results have exhibited some interesting characteristics of bio-based material by producing excellent results. Bio-based materials can be selected instead of artificial materials to achieve high production

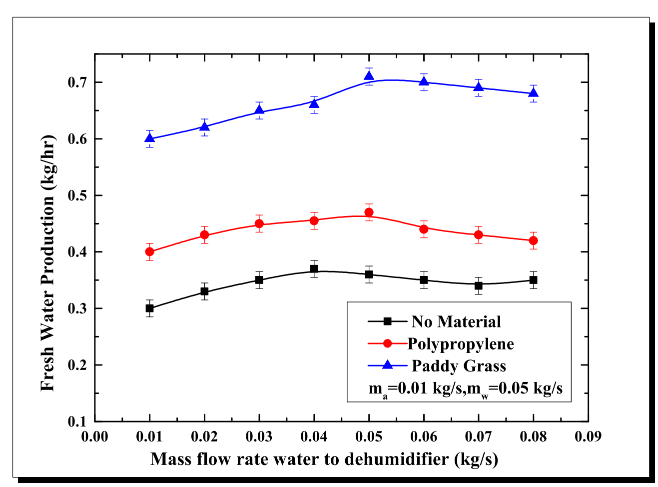


Fig. 11. Variations of cooling water mass flow rate on fresh water production.

rates and cost-effective and reliable operation of humidification and dehumidification desalination plants. Since the results of this study display low GOR value of the system, it is recommended to adopt regeneration technology in future research works.

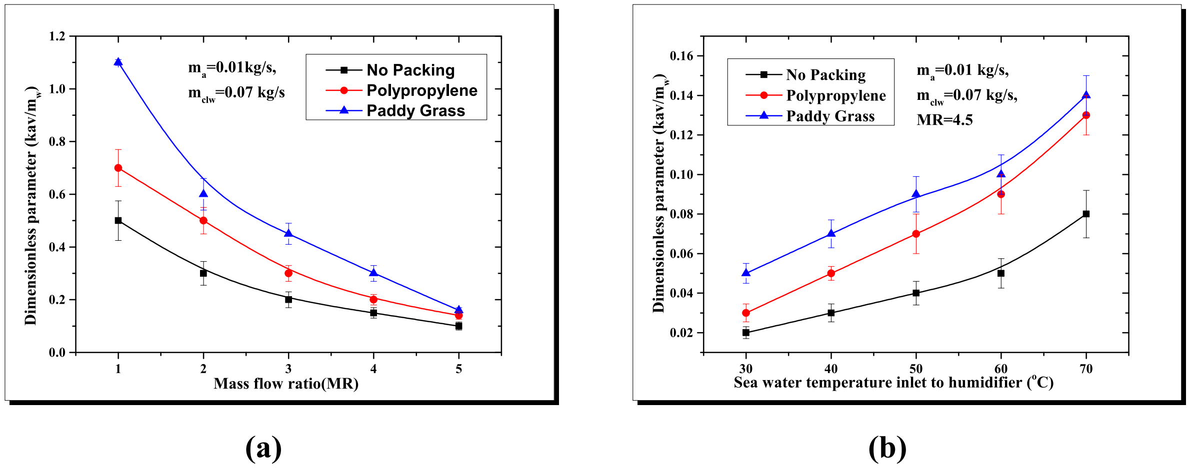


Fig.12. Effect of dimensionless parameter on (a) Mass flow ratio (b) Sea water temperature inlet to humidifier.

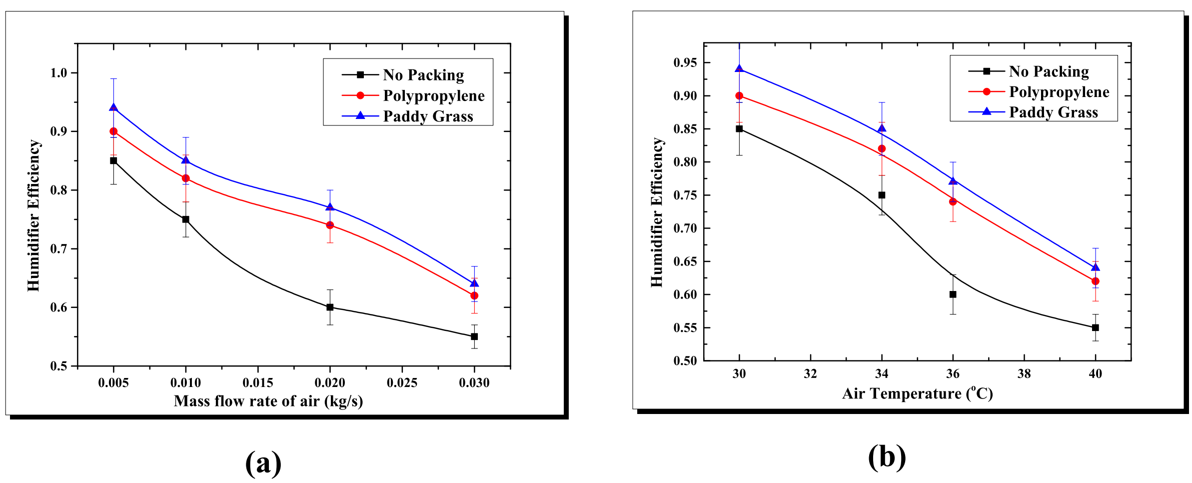


Fig. 13. Effect of humidifier efficiency on (a) Mass flow rate of air (b) Air temperature inlet to humidifier.

CRediT authorship contribution statement

Kumara Thanaiah: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Veershetty Gumtapure:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision. **Gamachisa Mitiku Tadesse:** Formal analysis, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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