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Performance Comparison of Tray, Bed and Integrated Drying Chamber in Closed Loop Heat Pump Dryer for Bermuda Grass

Ashok Kumar M[1,*], *Kumaresan* G[2], *Sivagaminathan* M[1], *Rajakarunakaran S*[1], *and Siva Subramanian* R[3]

[1]Department of Mechanical Engineering, Ramco Institute of Technology, Rajapalayam, Tamil Nadu, India
[2]Department of Mechanical Engineering, Bannari Amman Institute of Technology, Sathyamangalam, Tamil Nadu, India

[3]Department of Mechanical Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, Tamil Nadu, India

Abstract. Drying plays a crucial role in various industries such as food production, agriculture, Siddha, Ayurveda, and medical fields. To achieve controlled drying conditions, a heat pump dryer is considered an effective method, allowing for precise control of parameters like temperature, humidity, and air velocity. In this study, a heat pump dryer was designed and constructed to investigate the drying characteristics of Bermuda grass (Cynodon dactylon) at different velocities (1.5 m/s, 2.0 m/s, and 2.5 m/s) using three types of drying chambers: fluidized bed dryer, tray dryer, and combined dryer (a combination of bed and tray). The heat pump system utilized R134a as the refrigerant. The performance of the heat pump dryer in the three drying chambers was analyzed using Bermuda grass as the drying product. The Moisture Removal Rate (MRR) was calculated for various combinations of velocity and drying chamber, and it was observed that the combined dryer achieved a higher MRR at all three velocities compared to the tray and fluidized bed dryers.

1 Introduction

Herbal leaves are very essential for manufacturing Siddha and Ayurveda medicinal products. Drying is an important process involved to preserve the herbal leaves for long period of time without any formation of fungi and also making it into powder form. Leaves drying methods are generally classified as Thermal, chemical, and special drying in which heat pump drying is one the methods of cabinet tray (bed) drying under the thermal forced convection method and this is environmental friendly, economically viable also best suitable for drying the herbal leaves [1].

* Corresponding author: ashokkumar@ritrjpm.ac.in

Heat pump drying offers control over important operating parameters such as air temperature and velocity, leading to improved drying rates and higher quality of dried products. It is particularly beneficial for drying heat-sensitive biomaterials, as it enhances survival rates, preserves color, improves rehydration properties, and maintains the hardness of the dried products [2]. To ensure uniform airflow during drying, a cylindrical drying chamber was designed and implemented in combination with a heat recovery unit within a heat pump dryer. Experimental tests were conducted using mint leaves at a temperature of 35°C and varying air velocities of 2.0, 2.5, and 3.0 m/s [3]. Another method to enhance the moisture removal rate (MRR) in heat pump drying of herbal leaves is by introducing vacuum conditions within the closed-loop system. This approach allows for improved drying rates, especially at lower temperatures, when the heat pump operates under vacuum pressure conditions [4].

The systems are utilized in various applications such as space heating, drying processes, desalination, and water heating [5]. The specific moisture extraction rate for banana slices is investigated at different temperatures within a closed-loop heat pump dryer [6]. The thickness of the slices significantly affects the drying rate and specific moisture evaporation rate [7]. The specific moisture evaporation rate is primarily influenced by the size, thickness, and density of the leaves [8]. A comparison is made between the rehydration and water activity of dried apples, as well as the specific moisture evaporation rates, in different drying processes such as electrically heated hot air drying at 45°C and 65°C, closed-loop reheat heat pump drying, and open space dehumidification heat pump drying. The findings show that heat pump drying exhibits lower specific moisture evaporation rates compared to hot air drying, while also resulting in better rehydration values and lower water activity for the dried apples [9]. It is noted that heat pumps are cost-effective heat recovery systems that can be combined with heat-driven ejectors to enhance efficiency by more than 20%. The incorporation of advanced compressor technology can further reduce energy consumption by up to 80% in heat pump systems [10].

The two-stage evaporator heat pump dryer demonstrates a 35% increase in heat recovery compared to the single-stage evaporator heat pump dryer [11]. Utilizing a neural network, it is determined that the conical air distributor achieves uniform air distribution and results in a faster drying rate compared to a flat plate distributor during the initial 60 minutes of drying [12]. The combined air-to-air heat exchanger and R134a heat pump system outperforms the air-to-air heat exchanger alone [13]. The performance of a modified heat pump dryer, where inert gases such as nitrogen or carbon dioxide are used as the circulating gas instead of atmospheric air, is compared to vacuum and freeze drying. Guava and papaya are utilized as samples in all types of dryers, and the modified heat pump dryer proves to yield high-quality dried products at a reasonable cost [14]. The drying temperature has an impact on the nutrient content of leaves, and it is recommended to maintain the maximum drying temperature below 50°C to preserve the optimal nutrient quality of moringa leaves [15]. In the proposed study, bermuda grass is employed as the test product, and the drying rates in tray, bed, and combination drying chambers are experimentally evaluated in a closed-loop heat pump dryer.

2 Material used

2.1 Materials

The grass used in the experiment study was purchased on the day the experiment was done in order to guarantee its freshness. In total, 9 kg of grass were purchased, 3 kg of which were used for the experiments, which lasted 30 minutes. The remaining grass was kept in a moist towel for the duration of the first and second trials to prevent natural drying.

2.2 Sample preparation

The newly purchased grass was first thoroughly cleaned under running water to remove any dirt, sand, or other foreign objects that might affect the performance study's results. The freshly cleaned grass was then wrapped in a dry cloth to remove any remaining water because, in order to get an accurate result, it must be placed in the drying chamber with no water left on it.

2.3 3D Design and development of heat pump dryer

2.3.1 Design

The heat pump dryer is consists of four major components, compressor, condenser, expansion device, evaporator. The schematic diagram of developed heat pump dryer is given in Fig. 1. The specifications all major components, dimensions of drying chamber, and capacity of fan are given in Table 1 and the range of measuring instruments are given in Table 2.

Table 1. Specification of Components

Components	Specification
Compressor	3 – Ton capacity – scroll compressor
Evaporator	3 – Ton capacity – Copper coil – Vertical finned type
Condenser	3 – Ton capacity – Copper coil – Vertical finned type
Expansion device	3 – Ton capacity expansion valve
Fan	1.5 kW capacity – 2 Nos.
Fabrication plate	G.I. Plate with 5 mm thickness
Tray - dryer	Stainless steel tray with the dimensions of 100 cm x 60 cm
Bed - dryer	Stainless steel tray with the dimensions of 100 cm x 60 cm x 60 cm

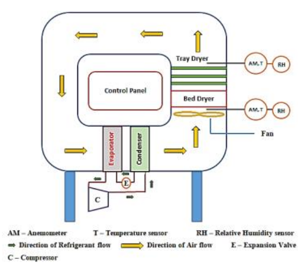

Fig. 1. Schematic diagram of heat pump dryer

Table 2. Range of Measuring Instruments

Measuring Instrument	Range
Anemometer	0 – 45 m/s
Temperature sensor	0 – 99°C
Humidity sensor	0 – 99 %

2.3.2 Experimental set up

The developed dryer is working based on the heat pump technology which consists of evaporator, compressor, condenser, expansion device. The evaporator, condenser, and expansion device are all installed inside a sealed duct where air is circulated with the help of fans without being affected by the atmosphere. The heat pump system's compressor is located outside of the duct. A uniform flow rate must occur in the drying chambers, hence two 1.5 kW fans are installed directly beneath the two drying chambers. The fluidized bed and tray drying chambers are positioned directly above the fans, and ductwork is used to deliver airflow from the drying chamber to the heat pump system's evaporator. The schematic diagram of the developed heat pump dryer is shown in Fig. 1. The bed and tray drying chamber are shown in Fig.2 and Fig.3

Fig. 2. Bed drying chamber

Fig. 3. Tray drying chamber

2.3.2 Working principle

In a dryer with a closed duct, air is circulated. As the air goes through the evaporator, it cools and reaches the dew point temperature, which causes the moisture in the air to condense. Once the air exits the evaporator, it passes through the condenser, where the refrigerant rejects heat to the air and heats it up, lowering the air's relative humidity. The drying product's moisture content can be absorbed by the low relative humidity air. As the products are dried in the drying chamber with low relative humidity air, the air's relative humidity rises as a result of the moisture being absorbed from the drying goods. The air comes out from the drying chamber flows in the direction of duct provided, reaches the evaporator and the cycle continuous until the required drying time. The process flow diagram is given in Fig. 4.

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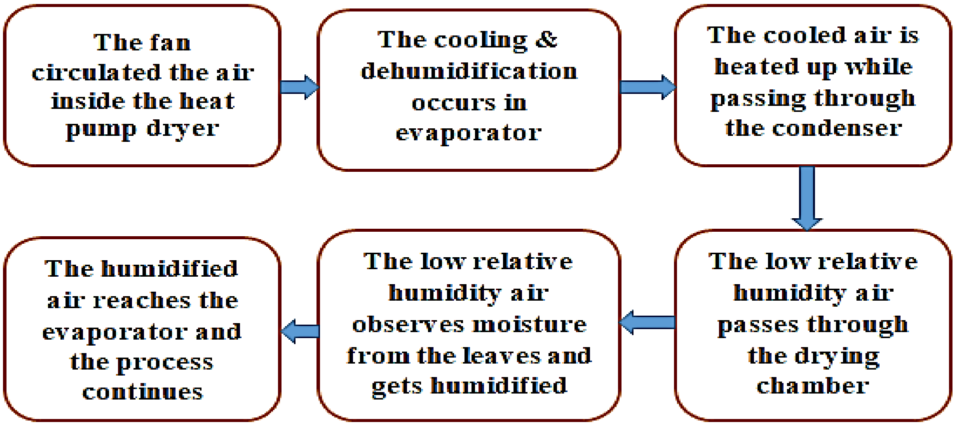

Fig. 4. Process flow diagram

3 Calculation

The Moisture removal rate or the evaporation rate of the drying process can be calculated by using the following equation.

$$\textbf{Moisture Removal Rate} = \frac{W_i - W_f}{T} \quad \textbf{in g/s} \tag{1}$$

Where,
W_i - Initial weight of curry leaves (g)
W_f - Final weight of curry leaves (g)
T - Time duration (s)

4 Result and discussion

4.1 Performance comparison of moisture removal rate at 1.5 m/s

The readings were taken for the duration of 30 minutes at 1.5m/s. In the case of tray drying method the average temperature and outlet humidity for 30 minutes are 44ºC and 34% and the drying rate is 0.42 g/s, fluidized bed method, the average temperature and humidity are 41ºC and 36% and the drying rate are 0.47 g/s and compound method, the average temperature and humidity are 46ºC and 44% and the drying rate is 0.56 g/s. The readings and results are given in comparison Table 3.

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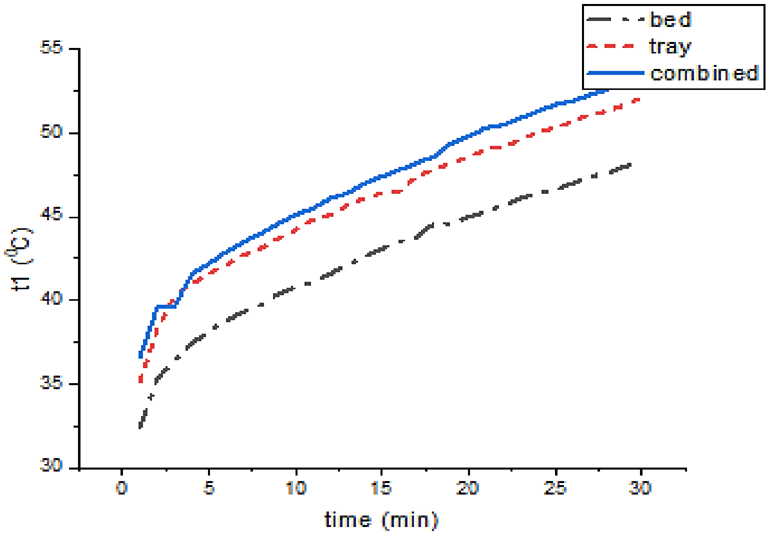

Fig. 5. Time Vs. inlet temperature at 1.5 m/s

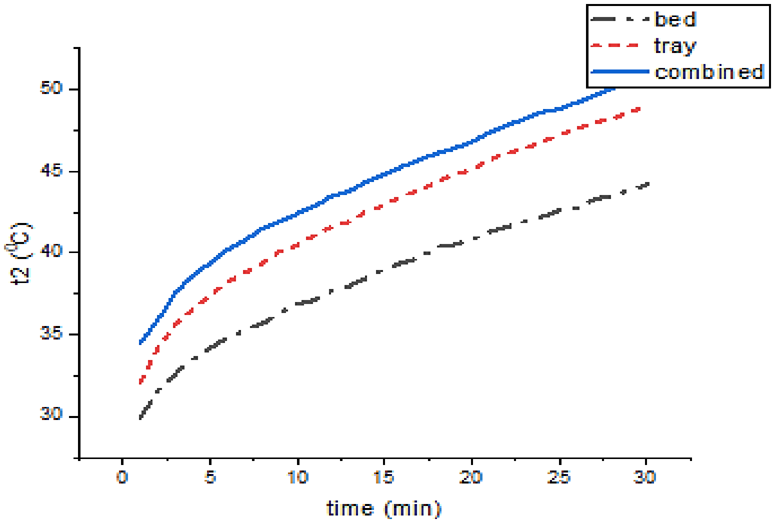

Fig. 6. Time Vs. outlet temperature at 1.5 m/s

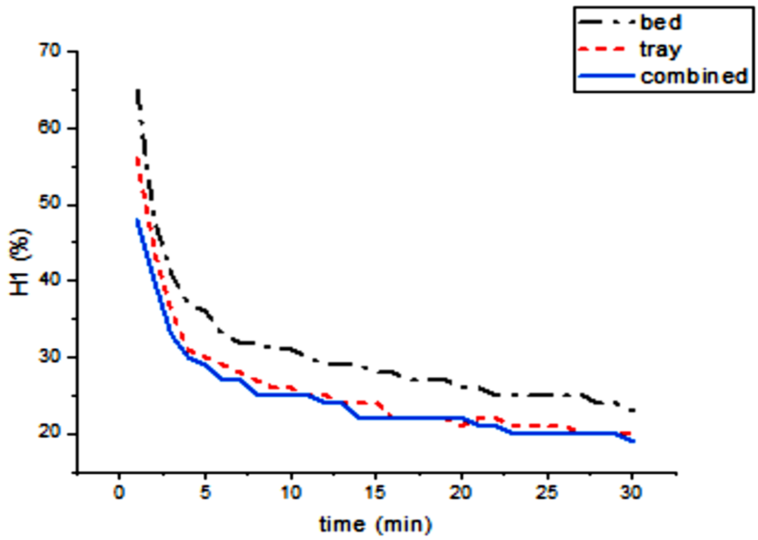

Fig. 7. Time Vs. inlet humidity at 1.5 m/s

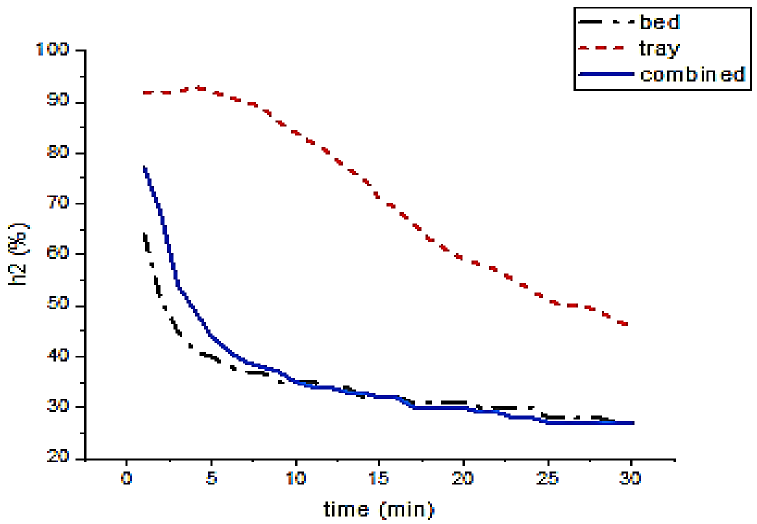

Fig. 8. Time Vs. outlet humidity at 1.5 m/s

Table 3. Moisture removal rate at 1.5 m/s

V=1.5 (m/s)	Int. wt. (kg)	Final. wt. (kg)	MRR (g/s)	Avg. Temp. (°C)	Avg. inlet humidity (%)	Avg. outlet humidity (%)
Bed	3	2.146	0.47	41	29	36
Tray	3	2.232	0.42	44	26	34
Combined	3	2.000	0.56	46	25	44

From Table 3, at 1.5 m/s, in the combined method 33% of moisture, Fluidized bed method 28% of moisture and in the Tray method 26% of moisture removed from the leaves in 30 minutes. Therefore, the moisture extraction rate in compound method is 19% greater than fluidized bed method and moisture extraction rate in fluidized bed method is 11% greater than tray method.

4.2 Performance comparison of moisture removal rate at 2.0 m/s

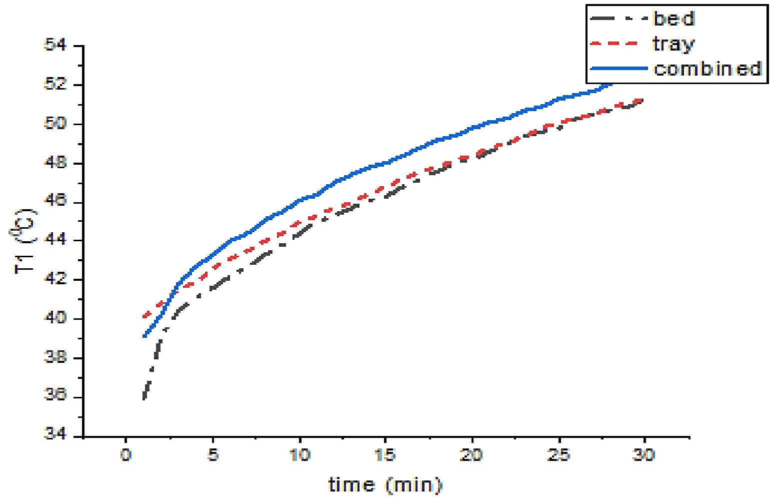

Fig. 9. Time Vs. inlet temperature at 2.0 m/s

The readings were taken for the duration of 30 minutes at 2.0 m/s. In the case of tray drying method the average temperature and outlet humidity for 30 minutes is 45°C and 35% respectively and the drying rate is 0.5 g/s. In the case of a fluidized bed method, the average temperature and humidity is 45°C and 40% respectively and the drying rate is 0.53 g/s. In the case of compound method, the average temperature and humidity is 46°C and 45% respectively and the drying rate is 0.65 g/s. The observation and MRR are given in Table 4.

Table 4. Moisture removal rate at 2.0 m/s

V=2.0 (m/s)	Int. wt. (kg)	Final. wt. (kg)	MRR (g/s)	Avg. Temp. (°C)	Avg. inlet humidity (%)	Avg. outlet humidity (%)
Bed	3	2.045	0.53	45	29	40
Tray	3	2.100	0.50	45	26	35
Combined	3	1.830	0.65	46	28	45

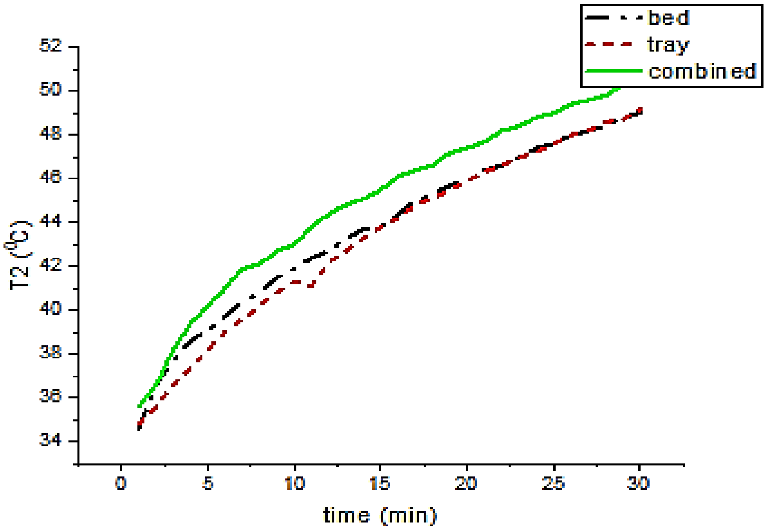

Fig. 10. Time Vs. outlet temperature at 2.0 m/s

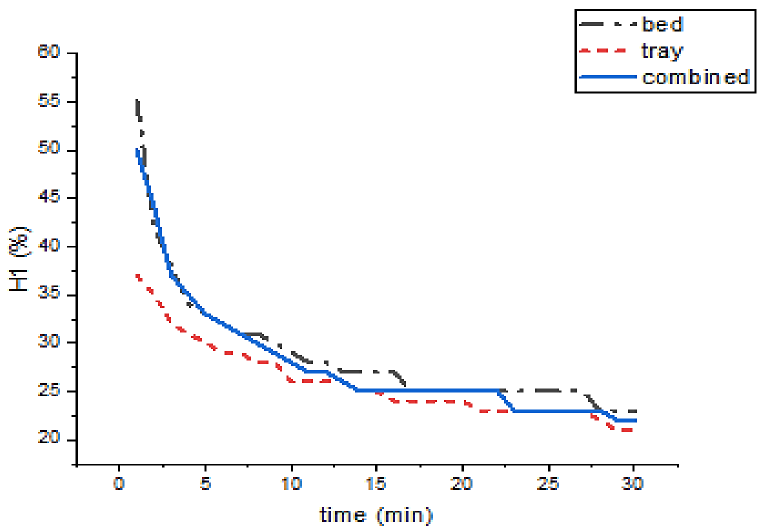

Fig. 11. Time Vs. inlet humidity at 2.0 m/s

From Table 4, at 2.0 m/s, the moisture removes in combined, fluidized bed and tray methods are 39%, 32% and 30% respectively in 30 minutes drying. Therefore, the moisture extraction rate in the combined method is 22% greater than the fluidized bed method which is 6% greater than tray method.

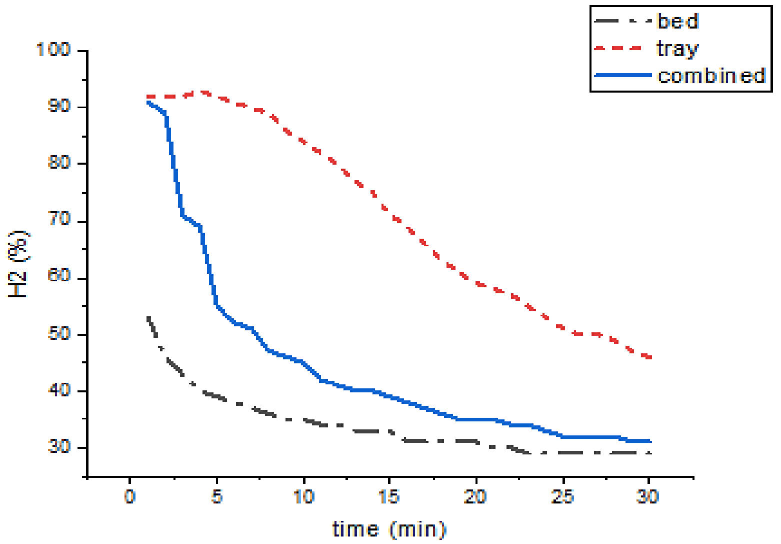

Fig. 12. Time Vs. outlet humidity at 2.0 m/s

4.3 Performance comparison of moisture removal rate at 2.5 m/s

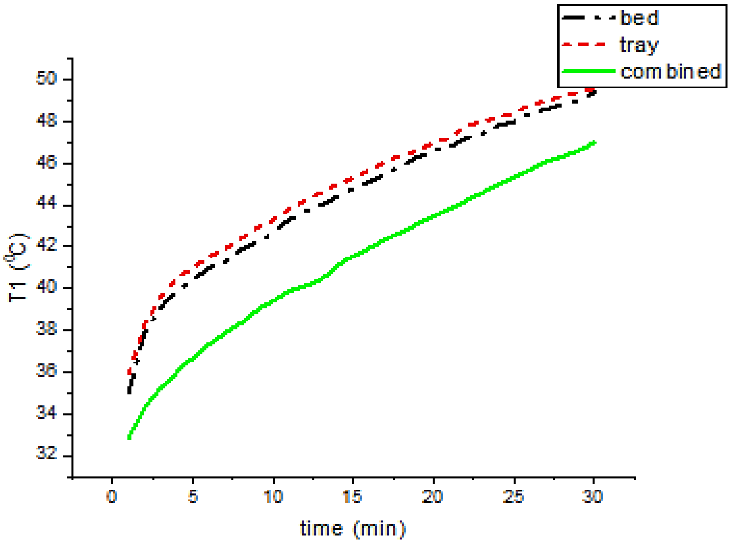

Fig. 13. Time Vs. inlet temperature at 2.5 m/s

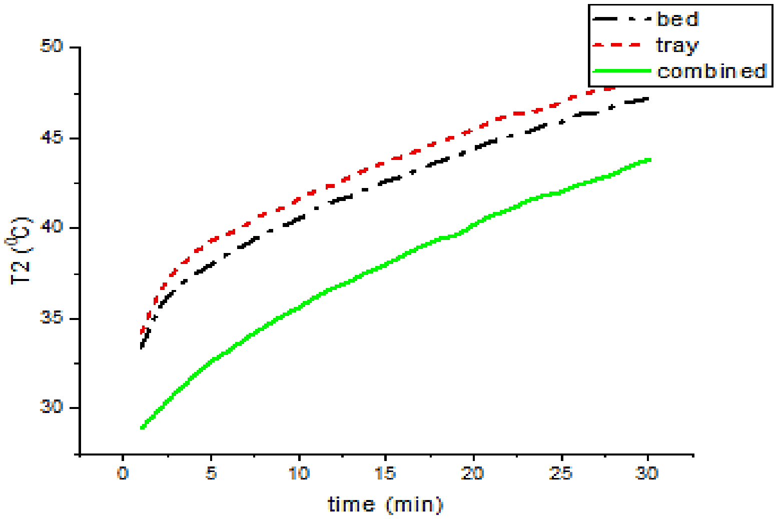

Fig. 14. Time Vs. outlet temperature at 2.5 m/s

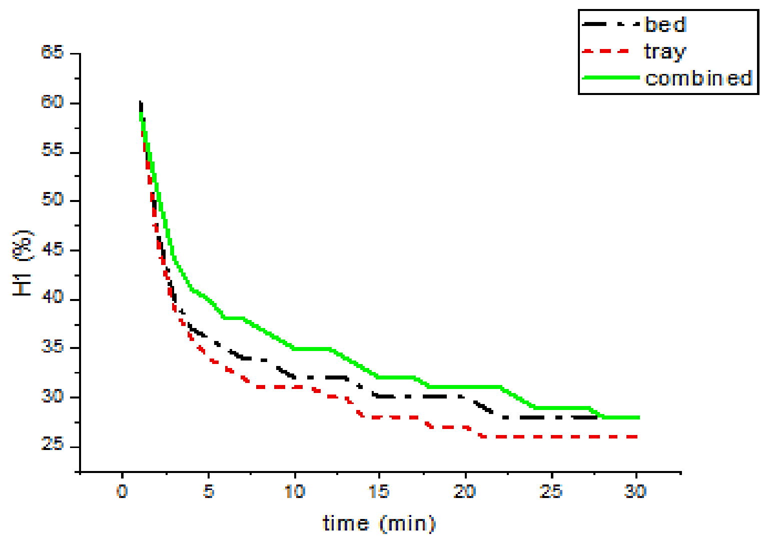

Fig. 15. Time Vs. inlet humidity at 2.5 m/s

Table 5. Moisture removal rate at 2.5 m/s

V=2.5 (m/s)	Int. wt. (kg)	Final. wt. (kg)	MRR (g/s)	Avg. Temp. (°C)	Avg. inlet humidity (%)	Avg. outlet humidity (%)
Bed	3	2.246	0.42	43	33	39
Tray	3	2.270	0.41	44	31	36
Combined	3	2.126	0.49	40	35	45

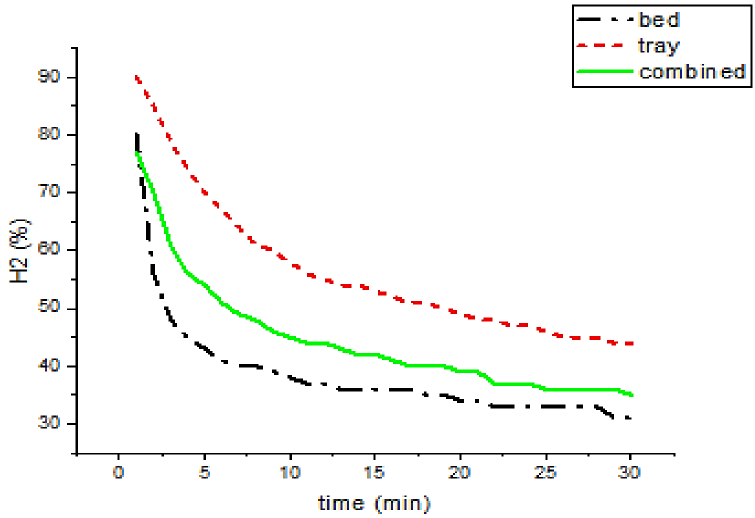

Fig. 16. Time Vs. outlet humidity at 2.5 m/s

From Table 5, at 2.5 m/s, the combined method removes 29% of moisture, fluidized bed removes 25% of moisture and tray method removes 24% moisture in 30 minutes. Therefore, the moisture extraction rate in the combined method is 16% greater in the fluidized bed method and the fluidized bed method is 2% greater than in the tray method.

4.4 Performance comparison of moisture removal rate with respect to inlet velocity

The Fig. 17 shows the graphical representation of performance comparison of bed, tray and combined method at 1.5, 2.0 and 2.5 m/s velocities. As shown in figure the moisture extraction of Bermuda grass is maximum at the velocity 2 m/s and at that the moisture removal rate in combined method is 22% greater than the fluidized bed method. The moisture extraction rate in fluidized bed is 6% greater than tray method, so that in the combined method, the moisture removal rate is 30% higher than the tray method. The better moisture removal rate is attained at combined method followed by fluidized bed and tray method at the drying air velocity of 2.0 m/s. The thickness of the spread of the leaves is varying in all three methods of drying, so that the inlet velocity of air has significant influence on the moisture removal rate. The better air and leaves contact duration is attained at 2.0 m/s than the other velocities, so that the higher drying rate is attained at that velocity. The combined method's moisture removal rate was higher than that of the other two techniques because the good air flow rate is achieved while the leaves spread out less thickly.

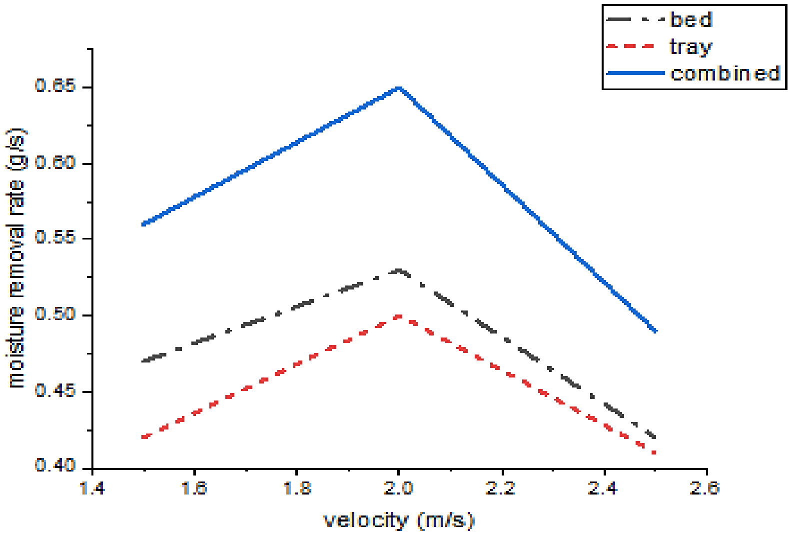

Fig. 17. Velocity Vs moisture removal rate (g/s)

5 Conclusion

The experiment to investigate the drying characteristics for Bermuda grass at three different velocities and in three different methods in closed loop heat pump dryers is conducted. Based on the results, the combined or both (Bed + Tray) way of drying Bermuda grass shows the highest moisture extraction rate at three different velocities followed by the fluidized bed and tray method of drying. On comparing all the methods in three different velocities the moisture extraction rate in combined type drying at 2.0 m/s is 0.15 g/s greater than tray type and 0.12g/s greater than fluidized bed type of drying. The moisture removal rate of combined type drying at 2.0 m/s velocity is 0.09 g/s and 0.16 g/s greater than 1.5 m/s and 2.5 m/s respectively. Therefore, Bermuda grass drying at 2 m/s velocity in combined method has the best performance in moisture removal rate. It has 24.61 % greater moisture removal rate compare to velocity of 2.5 m/s and 13.84 % higher compare to velocity of 1.5 m/s. The optimum air velocity for achieving better drying rate is 2.0 m/s at transient heat flow condition. The moisture removal rate varying with respect to velocity which has significant influence on drying rate and at transient heat flow condition the temperature increases with time during drying process.

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