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Experimental Investigations of Thin-layer Drying of Leaves in a Heat-Pump Assisted Tray-type Batch Drying Chamber

A.K. Babu[1,*] – G. Kumaresan[2], – V. Antony Aroul Raj[3], – R. Velraj[2]
[1] Easwari Engineering College, Department of Automobile Engineering, Chennai, India
[2] Institute for Energy Studies, Anna University, Chennai, India
[3]Easwari Engineering College, Department of Mechanical Engineering, Chennai, India

The design of a batch drying chamber with multiple trays for the thin-layer drying of fragile, heat-sensitive food materials, such as edible leaves, is a challenging task. It is essential to ensure good air distribution with minimum pressure drop in all the compartments of the drying chamber to obtain uniform drying of the product. In the present work, a drying chamber that was optimized from different configurations using computational fluid dynamics (CFD) software was fabricated and tested in the heat pump dryer. The experimental investigation was carried out with an optimized configuration for the temperature range of 50 °C to 60 °C, the relative humidity range of 20 % to 12 %, and air velocities of 1.41 m/s, 2.39 m/s, and 3.24 m/s. These optimal operating conditions were chosen based on an extensive literature survey on leaf drying. It was found that the drying process took place only in the falling rate period, fully controlled by the mechanism of liquid diffusion. The effects of air velocity on the performance parameters of the dryer were studied. Calculations based on the mean average parameters of the experimental data showed that a relatively higher heat utilization factor (0.17), moisture extraction ratio (0.375 kg/h), specific moisture extraction ratio (0.1529 kg/(kWh)), coefficient of performance (4.60), drying efficiency (76.23 %) and lower specific energy consumption (1.16 kW/kg) were obtained for a moderate drying velocity of 2.39 m/s in the heat pump drying process due to higher convection mass and heat transfer effects. Drying curves were plotted for different drying conditions and discussed. The findings were in agreement with those of many earlier research studies listed in the references section. The tested drying chamber can be used for drying all kinds of leaves in a heat pump dryer.

Keywords: Amaranth leaves, batch dryer, heat pump dryer, coefficient of performance, thin-layer drying

Highlights

- *A drying chamber optimized from different configurations using computational fluid dynamics (CFD) software is fabricated and tested in a heat pump dryer for drying Amaranth leaves.*
- *Good air distribution with minimum pressure drop is ensured in all the compartments of the newly designed drying chamber to obtain uniform drying of the product.*
- *The drying process of batches of spread-out material takes place only in the falling rate period.*
- *Better results are obtained for a moderate drying velocity of 2.39 m/s in the heat pump drying process.*
- *Air velocity, relative humidity, and the drying temperature are found to influence the rate of drying mutually.*
- *The newly designed drying chamber is suitable for drying all kinds of leaves in a heat pump dryer.*

0 INTRODUCTION

Amaranth leaves are a storehouse of many phytonutrients, antioxidants, minerals, and vitamins that are essential for good health and wellness. Fresh Amaranth leaves are one of the richest sources of vitamin C; 100 g of fresh leaves carry 43.3 mg or 70 % of the recommended daily intake of this vitamin. Vitamin C is a powerful water-soluble antioxidant that plays a vital role in healing wounds and helps the body fight and ward off viral infections [1]. Amaranth leaves can be dried all year round in India, and a few thousand tons are exported annually. Fresh Amaranth leaves can be easily dried in a tray dryer without degradation.

When hot air is blown over wet food, heat is transferred to the surface, and latent heat of vaporization causes water to evaporate. Water vapour diffuses through a boundary film of air and is carried away by moving air. Different drying methods are applied for drying Amaranth leaves. When dried in the open air, the drying time is about 10 days to 12 days. There are some disadvantages associated with the open-air sun drying of Amaranth leaves, which are related to the contamination with impurities, such as airborne dust, soil, sand particles and insects. Also, the process is weather-dependent, and accompanied by bleaching due to ultraviolet (UV) and chlorophyll depletion [2]. The drying process also involves a lot of material handling and manual labour, and the drying time can be quite long. Non-uniform and delayed drying process significantly changes the leaf colour, which results in a lower price in the market. Rainfall and windy weather can hamper the complete drying process. Therefore, the drying process is generally undertaken within closed equipment to improve the

*Corr. Author's Address: Easwari Engineering College, Bharathi Salai, Ramapuram, Chennai 600 089, India, ayya_krish_babu@yahoo.com

quality of the final product. With this controlled, low contact time drying process, vital nutrients, as well as the inherent colour and low volatile fragrance components, are retained to the maximum extent possible in the final dried materials within its limiting moisture levels for longer storage periods [3]. Once-through drying is a simple method, but obtaining all of the above-mentioned controlled conditions while maintaining high drying rates and heat efficiency with a short retention time of the material to be dried is difficult.

There are many closed-type once-through dryers used for dehydration of leaves. Efficiencies are generally higher for heat-pump drying (95 %) compared to vacuum drying (less than 70 %), and hot-air convective drying (between 35 % to 40 %) [4]. Also, a medium-range of temperatures (40 °C to 60 °C) and low relative humidity (12 % to 20 %) for safe drying of heat-sensitive leaves have been achieved experimentally in a heat-pump dryer (HPD) [5].

Benedicic [6] observed that drying products in a condenser dryer, which includes a fan, a heat-pump, and air duct, was complicated as all drying parameters, such as product moisture content, ambient temperature and humidity conditions, temperature and humidity, in the process were varied and mutually influenced each other during the drying operation. He also found that a controlled air-flow system was suitable for drying products of higher density and drying was also more economical in a condenser dryer. Cerci et al. [7] designed a drying chamber for drying zucchini, which distributed hot air uniformly. Aktas et al. [8] reported that a high velocity of drying air (3 m/s) had the lowest drying time for mint leaves. Their findings were supported by Premi et al. [9] for drumstick leaves and Kumar et al. [10] for mint leaves. Doymaz et al. [11] reported that optimum drying air temperature (50 °C to 60 °C) resulted in significantly reducing drying time for dill and parsley leaves. Their findings were in line with those of Rayaguru and Routray [12]. Hossain et al. [13] found that low relative humidity (20 %) played an important role in reducing the moisture content of herbs (89 %wb) (wet basis) to safe final levels (9 %wb). Fatouh et al. [14] observed that drying air temperature and air velocity had a significant effect on the drying rate. From their experimental investigation on drying herbs using HPD, it was noted that moderate air temperature (55 °C) and air velocity (2.7 m/s) resulted in the maximum drying rate. Almost all the research studies on leaf drying indicate that drying occurs in the falling rate period. This is usually the longest period of drying operation. Constant rate period was observed only in a few cases [2].

In the present work, a drying chamber that is optimized from different configurations using computational fluid dynamics (CFD) software is fabricated and used in the heat pump dryer [15].

The main objective of this research is to investigate the effect of a new batch drying chamber in a tray dryer using a closed-loop heat pump drying process (herein known as heat pump assisted tray dryer (HPATD)) on overall dryer performance for leaf drying.

1 METHODS

1.1 Sample Preparation

Fresh Amaranth leaves were purchased from a local wholesale market in Chennai, Tamil Nadu, India. The leaves were first washed clean with running water and sorted to remove the unwanted parts, such as stems and older leaves. Three trays were used for the study, and each tray was loaded with 0.5 kg of leaves. Most of the procured leaves were of uniform maturity and good quality.

1.2 Dry Matter

The dry weight of the leaves was found by drying samples in a drying oven at 105 ± 2º C [16]. After consecutive measurements, the samples were considered to be dry when the weight change was below 1 %.

2 EXPERIMENTAL PROCEDURE

2.1 Experimental Setup

The experimental analysis with HPATD was carried out based on the conditions mentioned in Table 1. These conditions were selected based on the in-depth literature survey [1], [5], [8], [14], [17] and [18].

Table 1. *Testing conditions for the drying of Amaranth leaves*

Conditions	Value
Temperature [°C]	30 to 60
Velocity [m/s]	1.47, 2.39 and 3.24
RH [%]	61.5 to 12.5

The technical specifications of various components involved in HPATD are mentioned in Table 2. The measuring devices/instruments used in this study. and their accuracy is given in Table 3.

Table 2. *Technical specifications of heat pump components*

Components	Specifications
Evaporator	Aluminum finned copper tube, 2.78 m^2, 5 fins/cm
Metering device (capillary tube)	91.5 cm length, 0.15 cm diameter, Number of circuits 2.
Condenser	Aluminum-finned copper tube, 3.60 m^2
Compressor	Hermetically sealed reciprocating type, cylinder volume 51.7 cm^3/rev, nominal power 2350 W, heating power 7330 W, 1.86 kW motor.
Fan	Axial type, 1330 rpm, 90 W, Hicool, China.

Table 3. *Measuring devices/instruments*

Measured quantities	Measurement devices		Measurement ranges	Accuracy
Mass of the product	Electronic weighing balance		0 kg to 20 kg	±2 g
Air velocity	Rotating anemometer [m/s]		0.1 to10	±0.1
Air temperature in the drying chamber [°C]	Electronic thermostat RTD PT100		–99 to +400	±0.1
RH of air in the drying chamber	Digital Humidistat		20 % to 90 %	±5 % RH
	Electronic thermo-stat RTD PT100		–99 to +400 °C	±0.1 °C
Refrigerant pressure [psi]	Bourdon tube	Evaporator side	–30 to 150	±2
		Condenser side	0 to 500	±10
Refrigerant temperature [°C]	Electronic thermostat RTD PT100		–99 to +400	±0.1
Power con-sumption [V]	Electrical power meter		180 to 260	–

2.1.1 Description of the Dryer

Fig. 1 shows the line diagram of the HPATD fabricated for the experimental work. The developed HPATD is a closed insulated chamber consisting of a dehumidifier unit, with an evaporator, hermetic compressor, expansion valve, and condenser at its lower portion and a drying chamber at its upper portion.

The refrigerant R134a is chosen as the working fluid and charged in the system. The dryer consists of three sections: the heating section, the airflow section, and the drying chamber. The drying chamber is horizontal, with annulus airflow parallel to the static drying material. The air is forced through an axial fan. Heated dry bulb temperatures are measured with the installed copper-constantan thermocouples. At the inlet and outlet of the drying chamber, the RH of air is measured by thermo-hygrometers.

A damper is inserted at the drying chamber outlet to alter the overall airflow rate. The velocity of airflow is measured using a digital anemometer (HTC, AVM-06, ±0.1 ms^{-1}, made in Taiwan) at the outlet of the drying chamber. A long diffuser with rectangular end cross-section with minimum pressure drop is used at the drying chamber air inlet. These two accessories help in ensuring a more uniform and straight airflow in the drying chamber. There is no inclination and no geometrical changes perpendicular to the airflow direction in the drying chamber. Uniform airflow distribution with a minimum pressure drop is a mandatory parameter because it has a significant effect on the homogeneity of the leaves being dried.

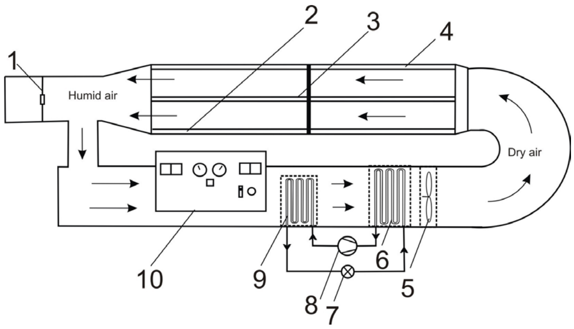


Fig. 1. *Experimental setup; 1 damper, 2 tray-1, 3 tray-2, 4 tray-3, 5 fan, 6 condenser, 7 expansion valve, 8 compressor, 9 evaporator, 10 control panel*

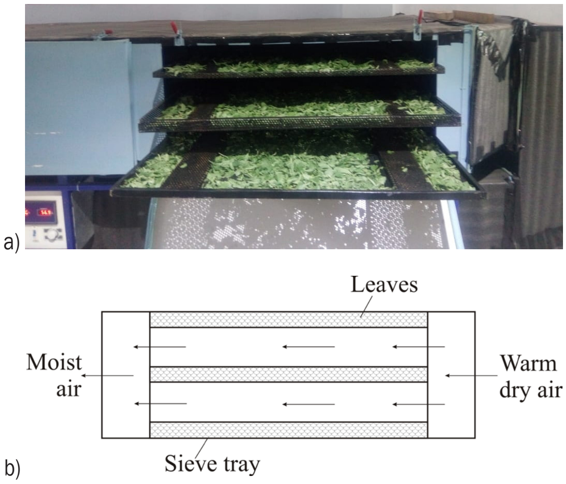


Fig. 2. *Drying chamber; a) photographic view, and b) schematic diagram*

The drying chamber has three perforated stainless steel trays placed parallel to each other. The dimensions of the drying compartment are 2.7 m × 1 m × 0.8 m. These trays are tightly embedded in the drying chamber to prevent all possible leaks, and the chamber walls are thermally insulated with Thermorex (6 mm) to reduce heat loss. Experiments are carried out at three levels of inlet air velocity (3.24 m/s, 2.39

m/s, and 1.41 m/s) with varying drying temperatures and percentages of RH.

Fig. 3. *Photograph of the experimental apparatus*

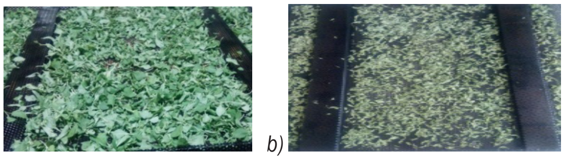
The major advantage of this setup is that the parameters (drying air temperature, drying air relative humidity, and drying air velocity) have been controlled to operate at constant optimized variable conditions.

2.1.2 Experimental Procedure

In this experiment, the drying chamber is maintained at a transient state condition in terms of temperature and relative humidity during the early part of the drying process, after which the operating conditions are almost stable. The humid air from the drying chamber outlet is passed over the evaporator of the heat pump, which acts as a dehumidifier. In this section, the humid atmospheric air loses moisture by cooling and giving up condensing heat to the vaporizing low-pressure refrigerant. The cooled dry air then passes over the condenser, where it is heated by the condensing high-pressure refrigerant vapour. The heated air then flows parallel to the drying product spread over the stacked trays. The drying air is circulated using an axial fan in a closed cycle, and fresh air is not allowed into the system. The velocity of airflow in the HPATD is altered with the help of a fan speed regulator. The dryer tested in this work is applied in transit drying [19]. The leaves can be dried during transportation using waste heat released from the radiator of the cooling system and the condenser of the vehicle air-conditioning system of the transit vehicle.

The gross weight of 1.5 kg fresh Amaranth leaves is used in conducting the experimental work. A uniform layer of 2 cm thickness is spread over all three trays, with each tray having about 0.5 kg. The initial moisture content of the Amaranth leaf is measured to be 89.3 % (wet basis) according to the procedure of ASAE standard S358.2, 1997 [20]. The drying cycle starts as soon as the trays are placed in the drying chamber. All trays with Amaranth leaves are weighed accurately at the beginning and the end of the drying cycle using an electronic balance of ±0.01 kg accuracy. Before starting an experimental run, the whole apparatus is operated for several hours for calibration purposes.

The initial moisture content has to be reduced up to 7 % to 10 % to obtain the desired final moisture content [2]. When the weight of the sample becomes constant, the experiment is stopped. The dryer is working with a closed circuit, and the moisture content of Amaranth leaves is measured based on water removed from the evaporator cooling coil of the heat pump. The moisture loss, drying time, the air temperature inside the chamber, relative humidity, air recirculation rate, and ambient temperature are considered as base data for the determination of moisture content, moisture ratio, drying rate, etc.



a) b)

Fig. 4. *A photographic view of Amaranth leaves; a) before drying, and b) after drying*

2.2 Modelling of Thin-Layer Drying

The drying performance of the dryer is determined based on heat utilization, the coefficient of performance, the quantity of the dried leaves, rate of drying, rate of consumption of electricity, and other operating conditions. Continuous dryers alone have constant rates of drying. The batch dryer can be evaluated only by overall utilities of power, operation time, heat energy cost, and the quality of the dried product.

2.2.1 Heat Utilization Factor

The heat utilization factor (*HUF*) may be defined as the ratio of temperature decrease due to cooling of the air during drying and the temperature increase due to heating of air. The *HUF* is determined by using Eq. (1) [21].

$$HUF = \frac{t_1 - t_2}{t_1 - t_o}, \tag{1}$$

where t_o, t_1 and t_2 are dry bulb temperature of ambient air, drying chamber inlet air, and drying chamber outlet air in [K], respectively.

HUF may be more than unity under certain drying conditions. *HUF* for a heat pump assisted dryer should be as high as possible to achieve a higher drying rate. At higher *HUF* values, moisture carried away from the leaves by the drying air is at maximum.

2.2.2 Coefficient of Performance

The coefficient of performance (*COP*) can be used to evaluate the amount of work converted into heat for two different system operations: cooling and heating. For a heat pump, the heat transfer from the system to the hot body is desired, and the coefficient of performance is expressed as [22],

$$COP = \frac{Q_{cd}}{W_c}, \tag{2}$$

where, Q_{cd} is the heat delivered by the condenser in [kW], and W_c is the power input to the compressor. When calculating the *COP* for a heat pump, the heat output from the condenser (Q_{cd}) is compared to the power supplied to the compressor (W_c). The range of *COP* is usually between 4 and 6 for heat pump drying.

Heat delivered by the condenser can be calculated from Eq. (3) [23].

$$Q_{cd} = m_a C_p (t_1 - t_3), \tag{3}$$

where m_a is the mass flow rate of air in [kg/s], C_p is the specific heat of air, in [kJ/(kgK)], and t_3 is the drying air temperatures at condenser inlet in [K], respectively.

2.2.3 Moisture Content

The percentage of moisture content (*M*) of Amaranth leaves is calculated by Eq. (4) [24]:

$$M = \frac{w_i - w_d}{wi} \times 100, \tag{4}$$

where, w_i and w_d are mass of the sample before drying and after drying.

The moisture content in freshly harvested leaves is 77 %wb to 91 %wb while that required for storage is 7 %wb to 10 %wb.

2.2.4 Moisture Ratio

Moisture ratio (*MR*) of Amaranth leaves is calculated by Eq. (5) [24].

$$MR = \frac{M_t - M_e}{M_i - M_e}, \tag{5}$$

where, M_t, M_i, and M_e are the moisture content at *t*, initial moisture content, and equilibrium moisture content, respectively. The values of M_e are too small to be compared to M_t or M_i for a long period and hence, Eq. (5) for *MR* is finally written as M_t/M_i.

2.2.5 Weight of Dry Material

Weight of dry material (w_d') is calculated by Eq. (6) [21]:

$$w_d' = w_i \left[\frac{100 - M}{100}\right], \tag{6}$$

where, w_i is the initial weight of the sample in grams and *M* is the moisture content of sample feed in %wb.

2.2.6 Drying Rate

The drying rate (*R*) in a gram of water per min per 100 g of dry matter during drying experiments is calculated by using Eq. (7) [21].

$$R = \frac{w_d}{t \times \left(\frac{w_d'[g]}{100}\right)}, \tag{7}$$

where *t* is the drying time in minutes.

2.2.7 Moisture Extraction Rate

Moisture extraction rate (*MER*) [kg/h] is defined as a kilogram of moisture removed per hour and indicates the dryer capacity or throughput rate. *MER* is given by Eq. (8) [25].

$$MER = \frac{(w_i - w_d)}{t}, \tag{8}$$

where, $(w_i - w_d)$ is the amount of water removed during drying.

2.2.8 Specific Moisture Extraction Rate

The specific moisture extraction rate (*SMER*) [kg/(kWh)] describes the effectiveness of the energy used in the drying process. *SMER* is defined as a kilogram of moisture removed per kilowatt-hour consumed energy and is related to the total power to the dryer, including the fan power and the efficiencies of the electrical devices. *SMER* is calculated by Eq. (9) given below [25].

$$SMER = \frac{(w_i - w_d)}{E_c}, \tag{9}$$

where, E_c is the total energy supplied in the drying process

2.2.9 Specific Energy Consumption

Specific energy consumption (*SEC*) [kW/kg], which is the reciprocal of *SMER*, is used to compare the energy efficiencies of different types of dryers. The *SEC* is defined as the total energy required to remove one kg of water. *SEC* is calculated according to Eq. (10) [25].

$$SEC = \frac{E_c}{(w_i - w_d)}. \quad (10)$$

2.2.10 Drying Efficiency

The effective heat efficiency is mathematically defined by Eq. (11) [13] and [21].

$$\eta_d = \frac{t_1 - t_2}{t_1 - t_w}, \quad (11)$$

where t_w is wet bulb temperature of drying air in [°C].

3 RESULTS AND DISCUSSION

The drying experiments were carried out in June and July 2018 in the Thermal Engineering Laboratory located in Easwari Engineering College, Chennai, South India. Each experiment was started at 9.00 a.m. and continued until the weight of the samples became constant. In the drying process, the temperature, the velocity, and relative humidity of the drying air had a considerable effect on drying and were the important parameters to determine the quality of the dried products. Velocity was taken as the constant parameter while varying temperature and relative humidity of the drying air, and the experiment was carried out. The dryer performance was evaluated, and drying curves were drawn to study the drying characteristics of Amaranth leaves.

3.1 Dryer Performance

The mean *HUF*, *MER*, *SMER*, *SEC*, *COP*, and drying efficiency values for three different velocities are tabulated in Table 4.

As shown in Table 4, the relatively best values (higher *HUF*, *MER*, *SMER*, *COP*, drying efficiency, and lower *SEC*) were obtained for a moderate drying velocity of 2.39 m/s in the heat pump drying process. The results obtained showed good agreement with the results of earlier studies available in the literature [18] and [26].

The *SMER* and *MER* values increased with a decrease in drying air velocity due to more drying potential of medium temperature air. The specific moisture extraction rate when using HPATD for drying Amaranth leaves was more at a high velocity of drying air (0.1529 kg/(kWh)) than low velocity (0.1512 kg/(kWh)). This was due to lesser energy requirement and higher drying potential of low RH air in HPATD.

The energy consumption of HPATD for 270 to 390 minutes of operation was found to be less (1.16 kW/kg to 1.27 kW/kg) when operating under different drying velocity conditions. It was observed that the variation of energy requirement was not much as the compressor had to operate for the same duration leading to almost equal energy consumption.

The maximum average *COP* of the HPATD was 4.60 for a moderate drying velocity of 2.39 m/s, which was relatively higher for better conversion of work into heat. Usually, *COP* increases with increasing air recirculation. Here, an increase in *COP* was observed for the moderate velocity of air, which was because of the increase in the temperature difference between temperatures at condenser and evaporator as a result of the decrease in velocity of air to the evaporator. Coefficients of performance below 4 are normally not acceptable for drying applications [13] and [27].

The drying efficiency varied with moisture content in the leaves for different velocities. As the drying progressed, the moisture content was reduced, and this resulted in a decrease in drying efficiency. The relatively higher drying efficiency of 76.23 % was obtained for a moderate velocity of air at 2.39 m/s.

3.2 Drying Curves

The effects of drying velocities on the drying process of Amaranth leaves are shown in Figs. 5 to 11, in which drying rate curves under different drying conditions are plotted. During the drying process, air

Table 4. *Dryer performance parameters*

Drying velocity, [m/s]	*HUF*	*MER*, [kg/h]	*SMER*, [kg/(kWh)]	*SEC*, [kW/kg]	*COP*	Drying efficiency, [%]
1.41	0.18	0.370	0.1512	1.27	4.23	72.12
2.39	0.17	0.375	0.1529	1.16	4.60	76.23
3.24	0.11	0.375	0.1529	1.26	4.46	74.34

velocity was kept constant, and the drying rate and drying time were continuously influenced by drying air velocity. It was experimentally confirmed that drying velocities had significant effects on the drying parameters. The drying rate curves indicated that the whole drying process occurred in the falling rate period.

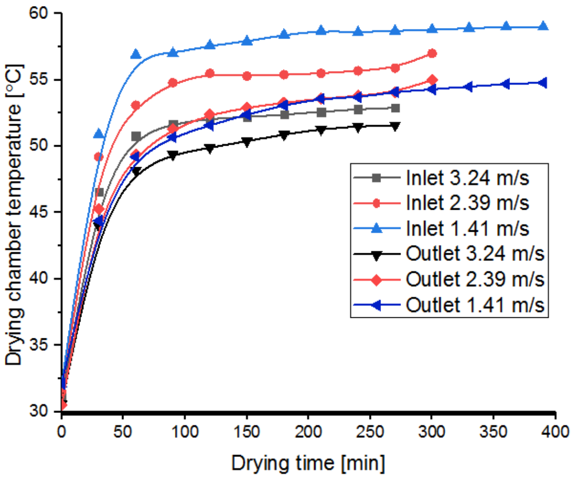


Fig. 5. *Variation of drying chamber at inlet and outlet air temperature with drying time*

3.2.1 *Effect of Drying Temperature*

Variation of inlet and exhaust temperature of the drying chamber with drying time for Amaranth leaves at different velocities is shown in Fig. 5. The temperature of drying air increased with time at the inlet and outlet of the trays and ultimately reached constant values. Initially, the temperature was low because the leaves were wet and released latent heat. As time progressed, the leaves began to dry, and the release of latent heat reduced, thereby increasing the drying air temperature inside the drying chamber. The maximum temperature attained by the air at the inlet of the trays was 59.1 °C, 57.0 °C, and 52.9 °C for the air velocities of 1.41 m/s, 2.39 m/s, and 3.24 m/s, respectively. The reason for the difference in temperature was the residence time of air in contact with the condenser surface area. As the residence time was slightly more with low velocity (1.41 m/s) of air, a higher drying temperature was observed. As leaves are to be dried in dryers using temperatures ranging from 40 °C to 60 °C, at which there will be no structural damage and nutrient losses [2], the dryer was designed to attain temperatures not exceeding 60 °C. The other reason was that when the temperature increased, the psychometric process moved towards the right on the chart, increasing the energy required to condense moisture at the evaporator.

The drying chamber inlet air temperature was varied during the initial stage of drying, after which the temperature was almost stable. The temperature was varied between 31.1 °C and 50 °C for the first few hours during which almost 20 % of the drying took place. It was implied that the temperature difference across the drying chamber was highest for the first few hours of operation and then decreased because the quantity of moisture removed during the second falling rate period was small. It was also inferred from the figure that the variation of air temperature across the drying chamber was significant when low air velocity was maintained. From Fig. 5, it is observed that, at any time of operation, the temperature difference was found to be 6 °C for low and high air velocity conditions at the inlet of the drying chamber whereas 4 °C temperature differences were observed from Fig. 5 at the outlet.

Since the reheat of a heat pump is constant inlet temperature decreases as the mass flow rate is increased as per $Q = m\,C_p \Delta T$.

Since the dehumidified air is recirculated, initially, because of the product moisture and thermal capacity, the temperature rises slowly to 50 ºC to 60 ºC. Once the product is heated, both the inlet and outlet temperatures remain constant.

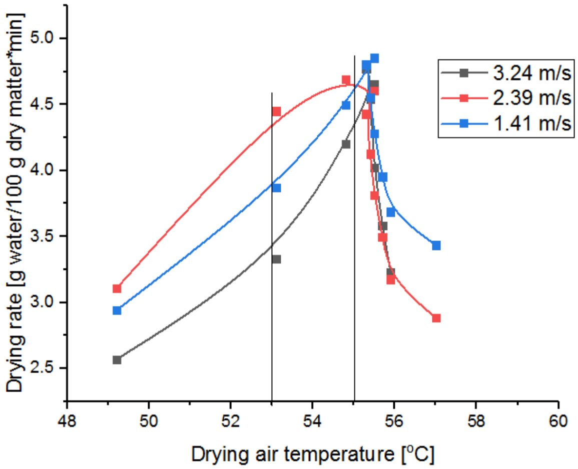


Fig. 6. *Variation of drying rate against drying temperature*

The experimental results showed that the drying air temperature had a significant effect on the expulsion of moisture content. As can be seen from Fig. 6, by increasing air temperature, the heat transfer rate between the heat source (drying air) and the material (Amaranth leaves) increased and led to faster moisture evaporation and shorter drying. In the temperature range of 53 °C to 55 °C, there was a significant increment in drying rate, as depicted in Fig. 6. This range was wider for low velocities of air (1.41 m/s), which was in agreement with the results of earlier studies on drying of amaranth leaves [28], and mint leaves [10].

For leaf drying, it was better to use drying temperatures of 50 °C to 55 °C. The temperature should never exceed 60 °C. The main reason for this was because higher temperatures would destroy important nutrients in the leaves. Without these nutrients, the leaves would lose much of their dietary importance.

3.2.2 Effect of Air Humidity

Fig. 7 indicates the relative humidity of air at the inlet and outlet of the drying chamber. The RH values of drying air at the inlet of the drying chamber were achieved from the initial values of 57.1 %, 61 %, and 54.8 % down to 12.5 %, 14.8 %, and 17.9 % for the air velocities of 1.41 m/s, 2.39 m/s and 3.24 m/s, respectively, by the end of batch drying. The corresponding temperatures were 59.1 ºC, 57 ºC, and 52.9 ºC, respectively. The initial high moisture content of the leaves and low temperature of drying air resulted in higher initial RH of the drying air, as seen in Fig. 7. The difference between outlet and inlet air RH was more initially due to the loss of water from the wet product.

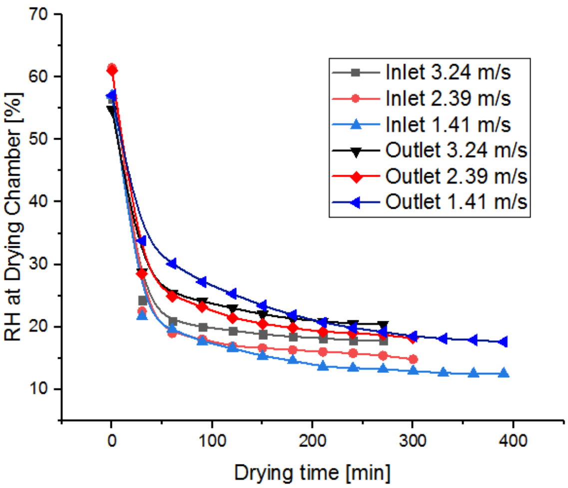


Fig. 7. *Variation of RH for drying time at inlet and outlet of the drying chamber*

The RH of air entering the drying chamber was maintained below 30 % with the dehumidification system of the HPATD in 30 min from the start of dryer operation for all drying velocities chosen, as seen in Fig. 7 [22]. In the closed air circuit of HPATD, the RH continued to gradually decrease and attained an almost constant value after 60 minutes. It was evident from the figure that the reduction of RH during the study was more for the low velocity of airflow (as drying temperature was comparatively more for 1.41 m/s). This showed that the flow velocity of air had the greatest effect on the reduction of RH and had an appreciable effect on the drying rate and drying time. It was, therefore, clear that the effect of RH on drying rate was a performance controlling factor in addition to air velocity and dry bulb temperature across the bed.

It is clear from the figure that the exit RH of air was always greater than the inlet RH of air. The moisture removal capacity of air was high at the beginning of the study as the leaves were wet and, further, the RH of air decreased because of the decrease of bound moisture content from the leaves. Fig. 7 also reveals that the difference in air RH at drying chamber inlet and outlet was more during the first falling rate period. It indicates that the drying rate was faster with higher air velocity during the first falling rate period.

3.2.3 Effect of Air Velocity

The drying rate is a strong function of the velocity of air over the products to be dried. Variation in moisture content as a function of drying time is shown in Fig. 8. After drying, the moisture content of the Amaranth leaf samples was reduced from an initial value of 89.3 %wb to less than 10 %wb. The variation of equilibrium moisture content of the leaves occurred based on the drying air velocity. Equilibrium moisture contents of 7.51 %wb, 4.19 %wb, and 9.09 %wb were achieved for the drying air velocities of 1.41 m/s, 2.39 m/s, and 3.24 m/s, respectively. The corresponding drying times of these experimental runs to achieve the above moisture contents were 390 min, 300 min, and 270 min. The lowest final moisture content was obtained by a moderate air velocity of 2.39 m/s. From Fig. 8 and Table 5, it is seen that the drying time needed to reach the equilibrium moisture content (EMC) was shortened notably with an increase in drying air velocity from 1.41 m/s to 2.39 m/s, and 3.24 m/s due to a larger driving force for mass transfer at a higher velocity of air, which was in agreement with the results of studies on drying of dill and parsley leaves [11], studies on drying Amaranth leaves using solar dryer [28], and studies on drying of crops [14]. However, the equilibrium moisture content of 4.19 %wb was obtained with a moderate velocity of 2.39 m/s, which was slightly higher than for 2.39 m/s. A velocity of 1.41 m/s allowed the leaves to dry reasonably well. However, when the velocity was increased to 2.39 m/s and 3.24 m/s, there was a noticeable improvement in the drying rate and drying time as the mass transfer rate was higher due to the larger driving force.

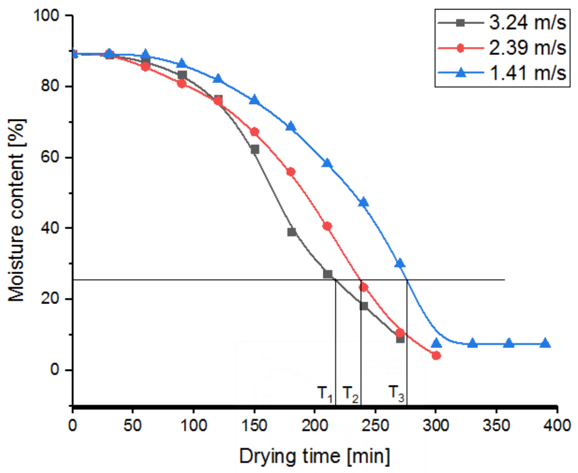


Fig. 8. *Effect of air velocity on moisture content of Amaranth leaves*

Table 5. *Equilibrium moisture content of Amaranth leaves*

Air velocity, [m/s]	Average drying air temperature, [°C]	Average relative humidity, [%]	Equilibrium moisture content, [%wb]
1.41	57.8	15.1	7.51
2.39	54.7	17.1	4.19
3.24	51.5	19.5	9.09

During the constant drying rate period, the air velocity needs to be high for the rapid initial evaporation of moisture from the surface of the leaves. Since drying progressed only with the falling drying rate period, the bound moisture gradually assumed importance. Therefore, the leaves required more energy and time to diffuse the bound moisture into the drying air and hence the amount of moisture that evaporated into the drying air decreased, as seen in Fig. 8. Thus the air velocity did not have to be high. At the same time, too low an air velocity increased the risk of non-uniform drying. According to the graph, the velocity of 1.41 m/s had no significant effect on the drying rate of Amaranth leaves.

In Fig. 8, a horizontal line was drawn to indicate constant wet basis moisture. At points where this line intersected the drying curves for each velocity, a thin line was dropped vertically. The three vertical thin lines met the horizontal axis for a time at points labelled T_1, T_2, and T_3. T_1 was the time for the sample dried at a velocity of 3.24 m/s to reach a certain specific moisture content. It was shorter than T_2, which was the drying time at a velocity of 2.39 m/s. T_3 was the time taken for drying at a velocity of 1.41 m/s, and was the longest drying time of the three. This clearly showed the impact of velocity on the drying of the Amaranth leaves for moisture removal and drying time.

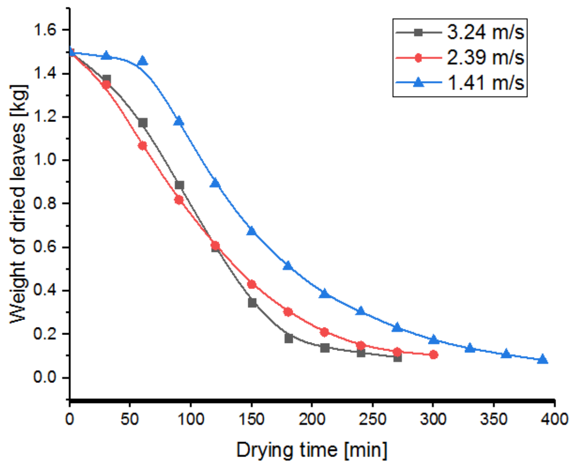


Fig. 9. *Effect of air velocity on the weight of dried leaves*

Fig. 9 shows the graph of the weight of the leaves during the time the drying tests were run with a curve for each velocity. It was seen that the weight of the leaves decreased faster with the air velocity of 2.39 m/s than it did for 3.24 m/s or 1.41 m/s.

3.2.4 Drying Rate

Fig. 10 shows the variation of drying rate versus drying time for different velocities. It was seen that the drying process took place only in the falling rate period, controlled by the mechanism of liquid diffusion. The constant rate drying period was almost absent. During the falling rate period, the drying rate decreased continuously with decreasing moisture content and increasing drying time. Usually, higher airflow velocity intensified drying rate change by the drying time. This result was in line with many earlier research findings on leaf drying [2], [4], [9], [13] and [16].

Change in air velocity had a strong influence on the evaporation of bound water from leaves and reduced drying time. Drying rates decreased as moisture content decreased. The results showed that the experiment with a moderate velocity of air had a higher drying rate and shorter drying time. The drying time of samples decreased from 390 min to 270 min as the air velocity was increased from 1.41 m/s to 3.24 m/s. The results were consistent with the results those obtained by Pal and Khan [22] for heat-sensitive crops.

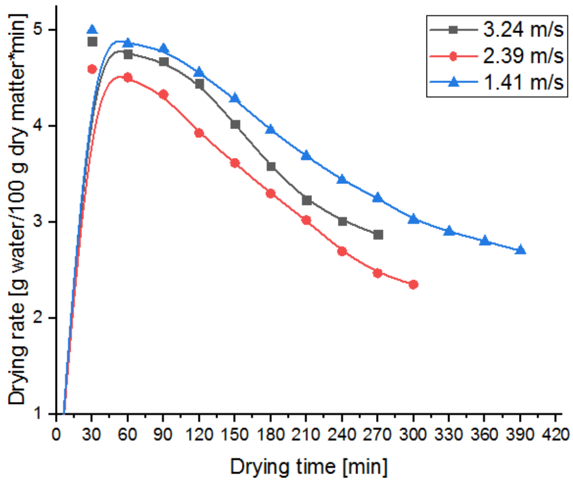


Fig. 10. *Effect of air velocity on drying rate*

It can be concluded that at a constant temperature and varied ambient percentage of relative humidity, the maximum possible drying rate was obtained by the moderate velocity of drying air (2.39 m/s) across the surface of the product, resulting in the rapid removal of moisture by evaporation from the product, which was because of the faster airflow along with suitable drying temperature (57 °C). It was seen from Fig. 10 that the drying rate curve showed a reducing trend for the highest velocity of 3.24 m/s when a low drying temperature of 52.9 °C was maintained. From the results, it was clearly understood that drying air velocity and drying temperature mutually influenced each other as well as the drying rate of Amaranth leaves.

3.2.5 Effect of Depth of Leaves in Trays

Fig. 11 shows the effect that the depth of leaves in trays had on the drying of Amaranth leaves for the moderate velocity of 2.39 m/s. As seen in the figure, the leaves placed in depths of 6 cm and 4 cm dried slowly when compared to the 2 cm depth, which was because the penetration of drying air through the leaves was relatively poor for a higher depth of leaves in the trays. T_1 was the time required for 2 cm depth of leaves to reach a specific moisture content. It was noticeably shorter than the time taken to dry 4 cm depth (T_2) and 6 cm depth (T_3), to the same moisture content. A thickness of 2 cm was hence found suitable to produce a considerable quantity of dried leaves from batch drying of Amaranth leaves.

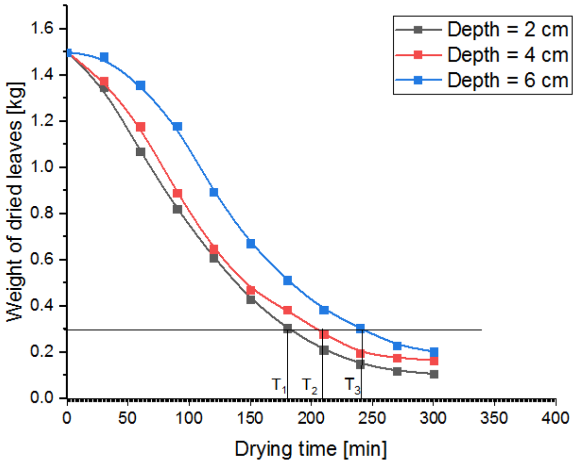


Fig. 11. *Effect of depth of leaves for the velocity of 2.39 m/s*

4 CONCLUSIONS

A drying chamber was designed, fabricated, and tested for closed-loop heat pump drying of Amaranth leaves. Experiments were conducted to examine the performance of an HPATD and determine some of the optimum operating conditions. The drying characteristics of Amaranth leaves at drying air velocities of 1.41 m/s, 2.39 m/s, and 3.24 m/s for the temperature range of 50 °C to 60 °C and relative humidity range of 20 % to 12 % were examined. The experimental results showed that

- The influence of the drying temperature was of more significance for the heat and mass transfer rate during the drying process rather than the convective effect of drying air.
- Drying rate curves indicated that the drying process took place mostly in the falling rate period.
- The velocity, temperature and RH of drying air were found to influence the rate of drying mutually.
- The experimental investigations confirmed that the moderate drying air velocity (2.39 m/s), moderate air temperature (50 °C to 60 °C), and low relative humidity (<20 %) had a significant effect on the expulsion of moisture content from Amaranth leaves.
- The results indicated that the increase in air temperature and a decrease in relative humidity

and velocity of the air improved the drying rate of amaranth leaves.

- The relatively best average values (higher *HUF*, *MER*, *SMER*, *COP*, drying efficiency, and lower *SEC*) were obtained for a moderate drying velocity of 2.39 m/s in the heat pump drying process.
- The investigation also established that a thickness of 2 cm was most suitable for batch drying of Amaranth leaves.

This dryer may be used for the effective drying of all edible leaves and other heat-sensitive crops as well.

As a result of this analysis, better drying air conditions were determined to obtain a high-quality dried product with less energy consumption.

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6 NOMENCLATURES

t_o dry bulb temperature of ambient air, [ºC]
t_1 dry bulb temperature of drying air, [ºC]
t_2 dry bulb temperature of drying chamber exhaust air, [ºC]
t_w wet bulb temperature of drying air, [ºC]
Q_{cd} heat delivered by the condenser, [kW]
W_c power input to the compressor, [kW]
m_a mass flow rate of air, [kg/s]
C_p specific heat of the air, [kJ/(kgK)]
T_C drying air temperature at the condenser inlet, [ºC]
T_D drying air temperature at drying chamber inlet, [ºC]
M moisture content of the sample, [%]
w_i initial mass of the sample before drying, [kg]
w_d final mass of the sample after drying, [kg]
M_t moisture content at ‘t’, [%wb]
M_i initial moisture content, [%wb]
M_e equilibrium moisture content, [%wb]
w_d' weight of dry material, [kg]
t drying time, [min]
E_c total energy supplied in the drying process, [kW]

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