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Recent Developments of Heat Pump Dried Agriculture Produce: An Overview of Technical and Theoretical Application

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ABSTRACT

Foods are very fundamental needs for all living beings. Cereals are harvested to meet the food requirements but it is difficult to simultaneously consume all foods. India, especially lack of consciousness of post-harvest technology and management for fresh food, large economic losses. Drying is a decrease in moisture from the product and is the most important process for storing agricultural products. The drying process involves the transfer of mass and heat in order to rapidly evaporate water from the product. Food qualities such as color, flavor, and structural alterations are changed by drying, nutritional value, and physical appearance and morphology. A heat pump is a heat generating device that transmits energy from heat by absorbing a low temperature range and released to a higher temperature. The heat pump consists of an expansion valve, two heat exchangers (evaporators and condenser) and a compressor. Heat pump calibration creates a regulated drying atmosphere (temperature and humidity) to improve quality of food product with low energy consumption. The main advantages of heat pump dryers (HPD) are the ability of the heat pump to recover energy from the exhaust and the ability to independently control the temperature and humidity of the dry air. This comprehensive review was conducted to study the drying behavior of various food materials under HPD in order to obtain high quality products.

Keywords Drying, Drying rate, Heat pump dryer, Horticultural products, Moisture diffusivity.

INTRODUCTION

Food is an organic substance that is consumed for nutritional purposes. Foods are of plant or animal origin and contain water, protein, fats, carbohydrates, minerals and other organic substances. Food spoilage due to microorganisms, chemical or physical agents, and food nutritional value, color, texture, and edibleness is susceptible to spoilage (Mullapudi *et al*. 2019). The history of "food preservation" dates back to ancient civilizations that first felt the need to preserve food after hunting large animals that the primitive army could not eat at the same time (Phoungchandang and Saentaweesuk 2011). It is defined as a process or technique performed to maintain internal and

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external factors that can lead to food spoilage. The main goal of food preservation is to extend shelf life while maintaining the original nutritional value, color, texture and taste. The overarching concept of all food preservation methods is to delay the action of the disease-causing bacteria or to kill them completely (Matthew *et al*. 2016). Food preservation involves various food preparation procedures to preserve food quality at desirable levels so that maximum benefits and nutritional value can be achieved (Amit *et al*. 2017). Food storage, processing and storage are essential to the continued supply of food during the season and off-season (Guiné *et al*. 2010).

Today, all countries look forward to meeting people's basic needs (food, clothing, shelter). Safe and hygienic food should be prioritized over all other basic needs. Only food preservation can meet the supply and demand of healthy food for a particular population (Khanlari *et al*. 2020). Drying, freezing, refrigerating, chemical storage and pasteurization are specific of the methods available. Drying is an ancient method of food preservation that can be achieved using sun drying, microwave heating, vacuum drying, and various other techniques (Minea 2008).

Importance of drying

One of the various ways of preserving food, drying is certainly the oldest and still widely used today. It is a technique that removes water from food by evaporation or sublimation, thereby limiting the amount of water available for chemical, enzymatic, or microbiological degradation reactions. The consumption of heat to evaporate the water confined in food and remove water vapor from the surface of the food is called drying. In doing so, it combines heat and mass transfer, both of which require energy (Cruz *et al*. 2015).

The main goal of dehydration is to preserve food and extend its shelf life by reducing moisture and activity. Avoid the need for expensive refrigeration systems for transportation and storage. Reduces the space required for storage and transportation.

It also allows food products to come in a variety of flavors and textures, giving consumers more choices when shopping for food (Guiné *et al*. 2010). Many new types of dryers have emerged that reduce energy consumption and operating costs.

Osmotic drying, vacuum drying, freeze drying, heat pump drying, microwave drying and spray drying are some of the techniques that can be used to get well-dried products. Due to its selective and volumetric heating effect, heat pump drying brings new qualities such as higher drying rate, higher final produce eminence and lower energy consumption (Sagar and Suesh 2010).

Drying and dehydrating fruits and vegetables is a traditional processing method that has long been used in the food business and has been well received by customers, but it definitely affects the appearance and physicochemical properties of the final product. Proper drying process and conditions are important for maintaining high nutritional value while maintaining a slightly different look and better flavor than fresh fruits (Danial *et al*. 2020).

Heat pump dryer

Heat pump dryers are known to be energy efficient when used in amalgamation with a drying operation. The main advantages of the heat pump dryer are the heat pump function that recovers the energy released and the function to control temperature and humidity of the dry gas. Many researchers have shown the importance of creating an accurate set of drying conditions to dry a wide range of products and improve their quality (Minea 2011). At the same time, stated that component and system design needs to be optimized to increase Energy-saving capacity of the heat pump systems.

Dryers that use convection as the primary mode of heat input to the dryer (with or without additional heat input from other heat transfer modes) can be fitted with a properly rated heat pump (HP). Batch dryers, tray dryers, or kilns (for wood) are the most commonly mentioned dryers used in combination with heat pumps, but other types are also available and rotary dryers (Ohlsson and Bengtsson 2002). A dryer that requires a large amount of dry air. B. Current dryers or spray dryers are not suitable for

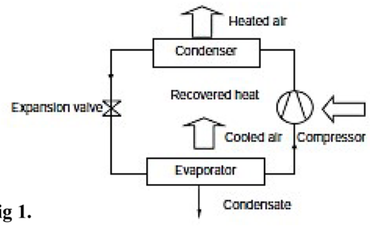

Fig 1.

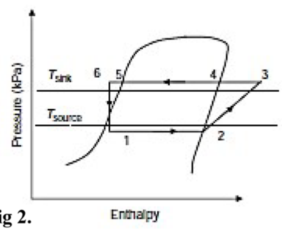

Fig 2.

Fig. 1. Schematic diagram of an air-to-air heat pump. **Fig. 2.** Pressure–enthalpy diagram of the pump cycle.

high voltage operation. Figure 1 shows a general categorization system based on the processing method for HPD, the number of drying stages, the number of heat pump stages, the type of auxiliary heat at the input, and the operation of dryer (Patel and Kar 2012). Many of these classes of heat pump dryers have been proposed and described over the last two decades.

The basics of a heat pump

A compressor, an expansion valve, and two heat exchangers (evaporator and condenser) constitute the fundamental parts of a heat pump system. Figure 1 shows a schematic diagram showing the operation of the HPD. Figures 2 and 3 show temperature-entropy and pressure-enthalpy diagrams for heat pump circuits (Sahoo *et al*. 2012). The heat pump circuit works as follows.

The cooling and dehumidification of the air occurs at the evaporator. The refrigerant, moving from point 1 to 2, engrosses warmness from the air and undergoes a two phase change from vapor– liquid mixture to vapor. Evaporation of the refrigerant is achieved by the gaseous escape of the molecules from the surface of a liquid while maintaining its temperature and pressure. The refrigerant vapor enters the suction line of the compressor at point 3. The electrical energy input to the compressor is converted to shaft work to raise the refrigerant's pressure vapor to that of the condenser at point 4. By increasing the vapor pressure, the boiling and condensing temperatures of the refrigerant is raised to a level higher than that of the heat sink temperature (the surrounding temperature). At this stage, the vapor is in a superheated state. After compression, the refrigerant vapor is directed to the condenser that is basically a heat exchanger to carry out the condensing process. The refrigerant first undergoes quick desuperheating change from superheated vapor to saturated vapor and then undergoes condensing process in the condenser. At the condenser, the refrigerant undergoes two phase condensation, changing from vapor to liquid phase. During this process, heat is released from the condenser and warms the surrounding air (Taseri *et al*. 2018).

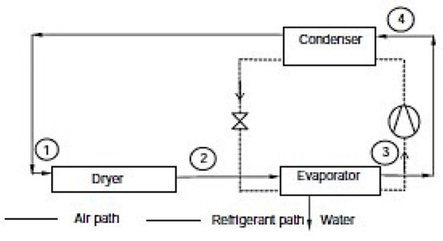

Fig. 3. Schematic representation of heat pump drying system.

Heat recovery occurs when the heat energy absorbed by evaporator and the operating energy of compressor are "pumped" to the condenser side to significantly heat the air. As soon as the steam refrigerant exits condenser and subjected to an additional super cooling step (points 5-6) in another heat exchanger. On the one hand, additional heat can be recovered due to the sensible heat of the air. Second, it reduces flushing when the refrigerant pressure in the throttle device drops. After the condensation process, squeezing devices such as valves, orifices, and capillaries are used to inflate the liquid refrigerant, reducing the pressure on the refrigerant surface to a boiling point below the boiling point of the heat source. After the expansion process, the refrigerant enters the evaporator in a two-phase state and the entire cycle repeats (Fatouh *et al*. 2006).

Principle

Figure 1 represents a schematic layout of various refrigeration components integrated with drying chamber. Inlet drying air passes through the drying chamber at point 1 and picks up moisture from the product. The moisture laden air at point 2 is then directed to evaporator coil. Two types of evaporator systems exist. One is a direct expansion coil whereby the refrigerant undergoes a two phase change from liquid to vapor to cool and dehumidify the air (Faal *et al*. 2017). The other is a cold water system that controls the flow of cold water to the coil for cooling and dehumidification. During the dehumidification process from points 2 to 3, the air is initially significantly cooled to the dew point. Further cooling leads to the condensation of water from the air. Next, latent heat of vaporization is absorbed by evaporator and refrigerant boils (Chong *et al.* 2014). The recovered heat is "pumped" into the condenser. The cooled and dehumidified air then absorbs the heat in the condenser and moves from point 4 to 1 to bring it to the desired temperature. The coefficient of performance (COP) identifies a heat pump's energy efficiency.

Recent development in HPD system

Authors studied the performance of solar dryers (SD) and solar assist heat pump dryers (SAHPD) for drying cassava chips. SD and SAHPD reduced the mass of cassava from 30.8 kg to 17.4 kg within 13 and 9 hrs, respectively, at average temperatures of 40°C and 45°C. The moisture content of cassava decreased from 61% (wet base) to 10.5% at a mass flow rate is 0.124 kg/s. The average thermal efficiency of SD and SAHPD is 25.6% and 30.9%, respectively. SD's average drying rate (DR) and specific moisture removal rate (SMER) are 1.33 kg/h and 0.38 kg/kWh, and SAHPD 1.93 kg/h and 0.47 kg/kWh, respectively (Mullapudi *et al*. 2019).

In present research contributes to the design of the drying chamber, uses three stainless steel cylinders with a circular nested shape that has several advantages. First, The item that needs to be dried can achieve a uniform flow of air penetrating the central cylinder from the outer perforated plate. The main purpose of this work is to analyze the drying properties of mint leaves in a new cylindrical drying chamber at low dry temperatures and emphasize energy analysis. The tests were performed at airspeeds of 2, 2.5, and 3 m / s, and a air temperature of 35 ° C. Mentha leaves were dried from 9 g water / g dry matter to 0.1 g water / g dry matter (Aktas *et al*. 2017).

Red varieties of Nashik onions were peeled, trimmed and cut to a thickness of 2 mm. Onion slices were dried in a heat pump dryer at 35°C (32% RH), 40°C (26% RH), 45°C (19% RH) and 50°C (15% RH). For comparison, the samples were also dried in a hot air dryer at 50°C (52% relative humidity). The drying rate increased with increasing dry air temperature, coupled with a decrease in relative humidity in the HPD. The page equation, which leads to a higher coefficient of determination and a lower mean square error, better, describes thin film drying of onion slices than the Henderson-Pavis equation (Sahoo *et al*. 2012).

Heat pump drying requires a short drying time of 360 minutes, has higher ascorbic acid and pyruvate retention, less color change, and higher compared to hot air dryers when the drying air temperature is the same as 50°C. Brought quality dry products. The drying air temperature for drying onion slices from 675.8 to 6% (db.) was 360 minutes at 50°C with a HPD, compared to 480 minutes with a hot air dryer. According to researcher's quality parameters such as rehydration rate, color retention, ascorbic acid content, and pyruvic acid content of onion slices obtained from a 50°C heat pump dryer were the highest of all samples (Patel and Kar 2012).

Most studies till date have used drying cabinets such as ovens, heat pumps and microwave dryers to dry the leaves. It is desirable to ensure better air distribution for uniform drying in the dryer design. In addition, the key goal of using heat exchangers and mass transfer at the identical time is to reduce pressure loss and increase mass transfer coefficient.

For solution of this problem, the current study focusing on computer-assisted solutions such as CFD for modeling drying problems, modeling with FEA, and choosing the right dryer. In the future, it will be a problem to find a new mathematical model or modify an existing mathematical model for use in drying in order to achieve more reliable and accurate results (Babua *et al*. 2018).

Heat pump dryers are a promising technology for maintaining product quality and reducing energy consumption during drying, especially for high value products such as fruits and vegetables. The application of HPD is to the next quality attributes such as improved microbial safety, improved color, vitamin C retention, improved volatile compounds, aroma and flavor compounds, hydration and texture. From study authors concluded that some of the factors such heat recovery, low energy consumption and high quality product that can make heat pump drying cost effective and energy efficient (Fayose and Huan 2016).

Dehumidifying trough and heat pump drying by one-stage drying and two-stage drying was developed by researchers. They observed that modified page model turned out to be the most effective to adapt the drying constant at the dry air temperature. The effective moisture diffusivity was range of 5.509 × 10^{-11} to 1.735 × 10^{-10} m2/ s and 6.101 × 10^{-11} to 1.944 × 10^{-10} m^2/s for tray dryer and heat pump dryer respectively. HPD introduced by two-step drying was able to decrease drying time at 40°C by 59.32% and increase the 6-gingerol content by 6%. Quality assessments with 6 gingerol contents, rehydration, and E* value showed the highest quality for HPD-dried sliced ginger incorporated by two-step drying at 40°C (Phoungchandang and Saentaweesuk 2011).

A HPD was designed, constructed and tested to evaluate the drying features of herbs and the dryer performance under various conditions. The drying air at a temperature of 55°C and a velocity of 2.7 m/s obtains the largest drying rate, according to the experimental results, while a high surface load of 28 kg/m^2 yields the smallest drying rate. At an air temperature of 55°C, an air velocity of 2.7 m/s, and a surface load of 28 kg/m^2, the maximum dryer productivity is around 5.4 kg/m^2 h. Researchers discovered that small-size plants without stems require less specific energy and dry faster than larger-size herbs (Fatouh *et al*. 2006).

Grape pomace was dried using heat pump technology at various dry air velocities and comparing the energy consumption of heat pump dryers and convection dryers, we can reduce energy consumption by up to 51%. For heat pump drying, increasing the air speed from 1.5 m/s to 2.5 m/s reduced the drying time by 69% but increasing the airspeed from 1.5 m/s to 2.5 m/s reduced energy consumption by 3%. Some of the bioactive properties of the sample were lost during the drying process at higher temperature and air velocity (Taseri *et al*. 2018).

In present study, researchers measured the EMC of mushrooms dried under vacuum conditions (0.2 bar) using a vacuum heat pump dryer at 50, 55, or 60°C and 10-75% relative humidity. Temperature, pressure and relative humidity affected the equilibrium moisture content of the fungal sample. Higher drying temperatures resulted in higher drying ratios and shorter drying times. Investigators also found that Peleg's model best predicts the equilibrium water content of shiitake mushrooms (Supakarn *et al*. 2018).

The apricot thin layer drying experiment using a dryer that combines heat and current was carried out in an experimental dryer. Four levels of engine power (25%, 50%, 75%, and 100%) were used in the drying trials, resulting in temperatures of 50, 60, 70, and 80°C in the drying chamber, respectively. In the drying chamber, the airflow was roughly 0.5 0.05 m/s. Fuel consumption at full load is high and uneconomical, and apricots decompose at temperatures above 80°C. Therefore, from an economic and product quality standpoint, 75% of the engine output is the optimum load for apricot drying. The average value of the effective diffusion coefficient was in the range of 1.6260 × 10^{-9} to 4.3612 × 10^{-9} m^2 / s when the apricot was dried at a temperature of 50 to 80 °C, an air velocity of 0.5 ± 0, and 05 m/s (Faal *et al*. 2017).

Heat pump technology is novel and useful with comparative advantages such as independent control of operating parameters (temperature and humidity), higher energy efficiency, higher drying performance, lower quality loss, It is a drying technique and is appropriate for dehydration of heat-sensitive fruit crops. This technique dehydrates the fruits by applying heat to the closed circuit of dry air, is unaffected by outside weather, maintains a stable temperature at any time of the year. The properties of the HP drying system on the diffusivity of some fruit trees have been reported and found that Deff values for some fruit crops being dried by heat pump dryers range from 10^{-7} to 10^{-11} m^2 / s (Luis *et al*. 2018).

Investigators (Chong *et al*. 2014) Worked on Drying apple cubes combined with a heat pump, vacuum microwave, and intermittent techniques. The application of combined heat pump and vacuum microwave when compared to other drying techniques, this drying provided the fastest drying time (about 50 % of the total drying time). Depending on the drying method employed, effective diffusivity varied from 3.522×10^{-8} to 1.431×10^{-6} m^2 /min and affected the drying time. The results showed that vacuum microwave combination drying (C/VM, HP/VM) produced the lowest values for chewiness and hardness. In addition, HP / VM drying resulted in the highest retention total polyphenols, antioxidant activity, and highest appearance quality.

Researchers developed, a HPD with a capacity of 3 tons is equipped with a bowl-shaped testing the drying chamber water removal rates of three different herb leaves Tulsi (*Ocimum tenuiflorum*) and Curry leaves (*Murraya koenigii*). Designed and manufactured using R134a as a refrigerant), and Bermudagrass (*Cynodon dactylon*). The primary operating factors that impact a closed circuit heat pump dryer's particular moisture evaporation rate are the circulating air velocity, temperature, humidity, and pressure. Experiments are performed under conditions of speed of 2.5 m/s, transition temperature, humidity, and circulating air at atmospheric pressure to assess the moisture elimination amount of the leaves of a given herb (Danial *et al*. 2020).

CONCLUSION

Various kinds of HPD systems are suitable for drying many items, particularly delicate ones to heat. Many researchers conclude that HPDs use energy more efficiently than electric dryers. The quality of heat pump drying products is also superior to outdated drying systems. In addition, desiccant-based heat pump dryers have been found to have greater energy savings than simple heat pump dryers in batch drying of heat-sensitive biological materials. The advantages of HPD stand out when compared to various traditional drying processes. Now is the time to develop and extend heat pump drying system applications around the world, especially in industrial and agricultural drying. The HPD market benefits globally in many sectors and helps reduce the high energy consumption that India has recently experienced.

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