Recent Applications of Heat Pump Dryer for Drying of Fruit Crops: A Review

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ABSTRACT
Heat pump (HP) dryers have been used as one of the useful and promising drying techniques in food industries owing to their low energy consumption and costs, high coefficient of performance (COP), high energy efficiency, high drying efficiency, low drying temperature, and time, and less quality loss of dried products. It can be operated over a wide range of temperatures and humidity, providing the optimum conditions for drying of heat-sensitive food materials (vitamins). Many studies were done on food products drying by various HP drying systems such as simple HP, solar-assisted HP, infrared-assisted HP, vacuum HP and ultrasound intensified HP dryers. This paper reviews the effect of different and recent HP drying methods on the drying performance and quality of dried apple, banana, grape, jujube, kiwifruit, and pineapple. Also, this study reported the suitable mathematical models for HP drying modeling of various fruit crops. The HP dryer provides high-quality dried fruits as their drying conditions can be controlled. In addition, combination of solar/infrared/vacuum/ultrasound techniques and HP dryer has been used as an efficient and rapid drying method compared to HP drying alone. The effective moisture diffusivity \( (D_{eff}) \) values lie within range of \( 10^{-7} \) to \( 10^{-11} \) m\(^2\)/s for some fruit crops during drying by HP dryer. Abbreviations: COP: Coefficient of performance; \( D_{eff} \): Effective moisture diffusivity; HP: Heat pump.

KEYWORDS
Drying efficiency; energy consumption; infrared; solar dryer

Introduction

In agricultural countries, large quantities of fruits (fresh or by-products) are dried to increase shelf life, preservation, reduce packaging costs, lower shipping weights, improve appearance, retain original flavor and maintain nutritional values. Conventional hot air drying technique is the most widely used method for production of dried fruits. However, it involves high energy costs, high dryer temperature and long drying time. In order to solve this disadvantage, new drying technologies, have been assessed recently (Amini et al., 2021; Salehi, 2020; Satorabi et al., 2021). One of these recent developments is based on heat pump (HP) technology, which permits an adequate energy management of the process (Castell-Palou and Simal, 2011; Singh et al., 2020).

HP drying, is increasingly used in food industries nowadays owing to its low energy consumption, less quality loss, high thermal efficiency, and high drying performance (Table 1). The energy-saving of HP drying is based on the reversed Carnot cycle principle (refrigeration cycle), it could recover energy from the exhaust and independently control the temperature and humidity of the air (Aguirre-Alonso et al., 2019; Chua et al., 2002; Colak and Hepbasli, 2009; Deng et al., 2015). In addition, with abundant amount of heat available in various natural sources and waste heat generated in various process industries, HP becomes an indispensable technology that can contribute toward a cleaner environment (Chua et al., 2010; Goh et al., 2011). Performance assessment and cost analysis of a HP fruit dryer...
Table 1. The effect of heat pump (HP) dryer conditions on the drying parameters and quality of fruit crops.

| Fruit or vegetable           | Air velocity | Drying temperature | Effective moisture diffusivity (m²/s) | Activation energy (kJ/mol) | The best model for drying kinetic modeling | Main results                                                                                                                                                                                                 | References                |
|------------------------------|--------------|--------------------|---------------------------------------|----------------------------|---------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| Apple, guava and potato      | 0.7 m/s      | 45°C               | -                                     | -                          | -                                           | Lower shrinkage and firmness of final dried products; high rehydration and maintain initial color                                                                                                            | (Hawlader et al., 2006b)  |
| Apple, potato and banana     | 1, 1.5 and 2 m/s | 35, 45 and 55°C   | -                                     | -                          | -                                           | Drying process in full air recirculation dryer is isolated from external environmental impacts, causing the dried product quality preservation.                                                                      | (Zlatanović et al., 2017) |
| Banana                       | -            | 61 and 66°C        | -                                     | -                          | -                                           | Higher energy efficiency of solar assisted HP drying (56.69%) as compared to simple HP drying (50.90%); The exergy efficiency of the solar assisted HP dryer was better as compared to simple HP dryer. | (Singh et al., 2020a)     |
| Banana slice                 | 0.8 m/s      | 50.25°C            | -                                     | -                          | -                                           | The highest values of specific moisture extraction ratio (0.212 kg/kWh) and coefficient of performance (3.059) were obtained at the highest drying air temperature.                                                | (Singh et al., 2020b)     |
| Grape pomace                 | 1.5, 2.0 and 2.5 m/s | 45°C               | -                                     | -                          | -                                           | Combination of HP, solar thermal and infrared dryers yields high efficient and quick drying; the highest energy efficiency (58.5%) and exergy efficiency (24%) for solar-assisted HP dryer; maximum moisture extraction rate for solar-infrared assisted dryer | (Taşeri et al., 2018)     |
| Hawthorn cake                | 1.5–3 m/s    | 60–65°C            | -                                     | -                          | Modified page                               | Lower energy consumption (51%); reduction in drying time.                                                                                                                                                       | (Duan et al., 2019)       |
| Jujube slices                | 2.0 m/s      | 55, 60 and 65°C    | -                                     | -                          | -                                           | Energy consumption of HP dryer decreased about 32.55% compared with the hot air dryer; higher specific moisture extraction rate (0.939 kg water/ kWh)                                                                 | (Hou et al., 2020)        |
| Kiwifruit                    | 1.0 m/s      | 45, 55 and 65°C    | 1.94 × 10⁻⁹ – 7.12 × 10⁻⁹ 14.04–20.39 | -                          | -                                           | High energy-saving (21.5%); improving the appearance quality; increasing L* index value and decreasing ΔE value and shrinkage ratio of kiwifruit slices.                                                             | (Mohammadi et al., 2019)  |
| Kiwifruit                    | 1.5 m/s      | 40°C               | -                                     | -                          | Weibull distribution                         | HP dryer and air recirculation increases drying rate of kiwifruit slices.                                                                                                                                      | (Lee et al., 2020)        |
| Lemon slices                 | 1.1 m/s      | 22°C               | 2.95 × 10⁻¹¹ – 3.73 × 10⁻¹¹ -         | -                          | -                                           | Contact ultrasound application in HP dryer is beneficial to accelerating dehydration rate and shortening drying time.                                                                                         | (Liu et al., 2020)        |
| Pineapple                    | 1 m/s        | 37, 40 and 43°C    | 3.78 × 10⁻⁹ – 6.57 × 10⁻⁹ 75.24       | -                          | Midilli & Kucuk et al.                       | The assistance of Coulomb force in HP dryer increased drying rate and effective moisture diffusivity (up to 26%), decreased drying time (by 40%), and saved total energy consumption (by 31.5%) | (Tunçkal et al., 2018)    |
(papaya glace) were done (Soponronnarit et al., 1998). In this study, energy consumption was 9.93 MJ/kg water evaporation and total operating cost was 0.38 US$/kg water evaporation of which 0.16 was energy consumption cost, 0.04 was maintenance cost and 0.18 was fixed cost.

Figure 1 represents a schematic of the reversed Carnot cycle components (two heat exchangers (evaporator and condenser), an expansion valve, and a compressor) integrated with the drying chamber. A HP dryer is made up of 5 main sections include compressor, condenser, evaporator, expansion valve and dryer. The inlet drying air passes through the dryer chamber and picks up moisture from the food product. The humid air from the dryer is passed over the evaporator of the HP, which acts as a dehumidifier. During the dehumidification process at evaporator systems, the air is first cooled sensibly to its dew point. Further, cooling results in water being condensed from the air. Latent heat of vaporization is then absorbed by the evaporator for boiling of the refrigerant. The recovered heat is “pumped” to the condenser. The cooled and dehumidified air then absorbed the heat at the condenser for sensible heating to the desired temperature (Chua et al., 2002; Queiroz et al., 2004). HP dryer efficiency and nonpolluting operation come from closed-air-refrigerant circuits and from its ability to fully recover the latent heat of moist air as it exits the drying chamber. As well as, due to its complicated system of the two interactive working fluids (refrigerant and drying air), the optimum design remains the question (Alves-Filho et al., 1997; Pal and Khan, 2008; Saensabai and Prasertsan, 2007). Designs of the HP dryer were investigated by Ogura et al. (2005) for the controllability of hot air production using a pair of a chemical HP dryer and Saensabai and Prasertsan (2007) for condenser coil optimization and component matching of HP dryer. Saensabai and Prasertsan (2007) reported that the closed-loop HP dryer with air by-passing over the evaporator is the best configuration. The proper coil design is 2-row, 2-circuit configuration with refrigerant mass flow rate of 16–20 g/s/circuit. The best air flow rate was found to be in the range of 0.6–0.8 kg/s and the corresponding number of coil modules were 8. The scope of Yang et al. (2013) study was to make a comparative simulation study on different intermittent HP dryings with respect to moisture diffusion, energy consumption, and drying time on Chinese cabbage (Brassica campestris L) seeds. In this drying process, percent energy saving over continuous drying was 48.1%. In addition, the best intermittent drying method was gotten, which the intermittency ratio is 1/3. In another study, Jangam et al. (2008) studied about dehydration of sapota fruit. In this study, the drying behavior of sapota pulp was studied using a convective dryer, a low-temperature HP dryer, and a freeze dryer. In case of HP, the drying is faster compared to hot air drying for the thickness of 4 mm at 40°C.

**HP Drying Applications**

HP dryer application is suitable for high-value products and its ability to produce controlled transient drying conditions in terms of temperature, humidity, and air velocity has been investigated to improve product quality and reduce drying costs (Haibo et al., 2017; Hwang et al., 2019; Patel and Kar, 2012; Xiaofei et al., 2017). Some researchers have compared HP dryer performance with other dryers. Strommen et al. (2002) reported that the HP dryers consume 60–80% less energy than conventional dryers operating at the same temperature. Rossi et al. (1992) reported that onion slices dried by an HP dryer consumed less energy in comparison to a conventional hot air dryer and presented higher quality. Prasertsan and Saen-Saby (1998) studied HP drying of agricultural materials and an economic analysis revealed that the HP dryer presented the lowest operating cost when compared with other dryers. Phoungchandang and Saentaweesuk (2011) reported that the HP dehumidified drying incorporated by the two-stage drying decreased the drying time of ginger about 59.32% (at 40°C) and increase 6-gingerol content by 6%. Drying kinetics of tomato by using electric resistance and HP dryers was studied by Queiroz et al. (2004). The authors reported that using HP dryers offer energy saving up to 40% as compared to electrical-resistance dryers without compromising the quality of the dried product. In addition, the Page model was used to predict drying time of tomato and statistical analysis showed that the model parameters were mainly influenced by dryer temperature. Drying kinetics of tomato slices dried by using a HP dryer was
examined by Coşkun et al. (2017). The drying rate of tomato slices were significantly affected by drying temperature and at the end of drying process, the highest mean specific moisture extraction ratio and coefficient of performance (COP) of HP dryer system were obtained as 0.324 kg/kWh and 2.71, respectively, at higher drying temperature (45°C). Gaware et al. (2010) dried tomato slices using five different dryer, include hot air, solar cabinet, HP, microwave vacuum, and freeze drying. During drying by HP drying only falling rate periods was observed. According to rehydration results, HP and microwave vacuum dried slices showed comparatively higher rehydration ratios than hot air and solar cabinet dried tomato slices. Use of low temperature, low relative humidity and inert gas flushing are the important features of HP dryer in preserving heat-sensitive compounds (vitamins and polyphenols) and retention of initial color (Hawlader et al., 2006b, 2006a; Potisate and Phoungchandang, 2010; Rayaguru and Routray, 2010). Tomato flavor from a HP dryer was characterized and compared to fresh and freeze-dried tomato samples for the retention of fresh flavor compounds (Jeyaprakash et al., 2016). The results showed that the volatile and sensory profiles of HP dried tomato were comparable to freeze-dried tomato, with good retention of fresh aroma.

Dryer design requires food characterizations, dryer type, drying rate, heat & mass transfer coefficients, and effective moisture diffusivity ($D_{eff}$) values. These values change continuously during drying due to changes in food fractions, particularly the water fraction. Heat and mass balance of both refrigerant and air circuits in all components of the system are used for development of mathematical models (Alves-Filho et al., 1997; Ogura et al., 2005; Pal and Khan, 2008; Singh et al., 2020a). Many researchers have performed various numerical and experimental investigation on the HP dehumidified dryer for drying of different biomaterial products. Simulation models of the HP dehumidified dryer were developed by Alves-Filho et al. (1997) for fruit and root drying. In addition, Achariyaviriya et al. (2000) developed a mathematical model of a HP fruit dryer to study the performance of HP dryers. The results showed that ambient conditions affected significantly on the performance of the open loop dryer and the partially closed loop dryer. Also, the fraction of evaporator bypass air affected markedly on the performance of all HP dryers. In addition, the authors reported that specific air flow rate and dryer air temperature influenced significantly the efficiency of all HP dryers. Exergetic assessment of drying of mint leaves in a HP dryer was studied by Colak et al. (2008). Results demonstrated that high exergy efficiency of the drying chamber was obtained at a temperature of 50°C and a drying air mass flow rate of 0.05 kg/s. The exergy efficiency values were obtained to vary from 76.03 to 97.24% at drying air temperatures of 40–50°C with drying air mass flow rates of 0.01–0.05 kg/s at a constant relative humidity of 16%. Ceylan and Gürel (2016) used solar-assisted fluidized bed dryer integrated with a HP for drying of mint leaves. In this study, HP system had a COP value of 5, and the energy and exergy efficiencies of the system were reported to be 50 and 26%, respectively.

One of the best ways to reducing in drying time of fruit crops is to provide heat by infrared radiation. Many studies were done on drying of fruit crops by different infrared drying methods (Salehi, 2020c, 2020a; Salehi and Kashaninejad, 2018b). Some researchers have been used combined infrared and HP dryer. Combination of infrared and HP drying has been used as an efficient and rapid drying method compared to HP drying alone (Aktaş et al., 2017; Deng et al., 2014; Lei et al., 2016; Wang et al., 2016; Xiaoyong and Luming, 2015). Performance analysis of HP drying and infrared assisted HP drying of grated carrot using energy–exergy methodology was studied by Aktaş et al. (2017). Energy efficiency in this study varied between 5.3 and 50% and infrared-assisted HP dryer saved 48.8% drying time compared to HP dryer. Maximum exergy efficiency was reported 66.8% while minimum exergy efficiency was reported 31.6%. This study shows a successful and efficient combination of HP and infrared heater in food drying.

Vacuum drying is a method of drying of food products with high drying rate because the vapor pressure of air in the product is lower than that at atmospheric air (drying at lower temperature) and water vapor is removed by a vacuum pump. In this method, the contact between the material being dried and oxygen is limited (Salehi and Kashaninejad, 2018a; Salehi et al., 2017). In recent years,
vacuum HP drying has been investigated as a potential method for obtaining high-quality dried products. This drying technique combines the advantages of both HP drying and vacuum drying (Artnaseaw et al., 2010b, 2010a; Ashok Kumar et al., 2020). For example, drying characteristics of the Shiitake mushroom and Jinda chili were investigated under varying conditions of the drying temperatures (50–65°C) and the vacuum pressures (0.1-0.4 bar) in a vacuum HP dryer (Artnaseaw et al., 2010b). The result indicates that the drying temperature and pressure significantly affect color degradation. Also, rehydration capacity of dried samples notably decreases with an increase in the vacuum pressure.

**Apple**

Apple represents the fourth most important horticultural crop for human nutrition in the world. Drying is one of the important preservation methods employed for storage of apple (Salehi, 2017; Salehi and Satorabi, 2021). In Hawlader et al. (2006b) study, apple, guava, and potato were dried in a HP dryer under inert environmental (nitrogen or carbon dioxide) conditions. Lemon juice and peel were used as natural inhibitors to prevent browning in air drying of apples. The authors reported that modified atmosphere HP drying at low temperature (45°C) and relative humidity around 10% led to better physical properties, such as reduced shrinkage, decreased firmness, and more porous structure of the materials, which resulted in higher rehydration. In another study, Perera (2001) reported that dried apples using modified atmosphere HP dryer showed good color and retention of vitamin C, and the total quality parameters of the dried product were higher.

Combined drying of apple cubes (15 mm) by application of HP, vacuum-microwave, and intermittent methods were investigated by Chong et al. (2014). The drying time was affected by effective diffusivity ranging from $3.52 \times 10^{-8}$ to $1.43 \times 10^{-6} \text{ m}^2/\text{min}$ depending on the drying technique used. It was reported that the HP vacuum-microwave drying gave the highest retained total polyphenol content, antioxidant activity, and the best appearance quality.
Banana

Due to the limited availability of conventional energy, researchers are focusing on the hybrid source HP dryer by using renewable energy. Solar-assisted HP dryer uses the cost-free solar energy (renewable); hence it increases the specific moisture extraction rate with lower specific energy consumption and also uses the advantage of non-conventional energy (Atalay, 2019; Hawlader and Jahangeer, 2006; Hawlader et al., 2008; Şevik, 2014; Singh et al., 2020a). Three important parameters that affect the solar-assisted HP dryer performance are solar radiation, compressor speed and the total load placed in the drying chamber (Hawlader and Jahangeer, 2006). The solar-assisted HP dryer system was designed and used for the drying of banana slices and obtained results were compared with the HP dryer system using R1234yf refrigerant (Singh et al., 2020a). The system COP, moisture removal from the product, drying rate, and specific moisture extraction rate are found better for the solar-assisted HP dryer than the simple HP dryer. The average drying rates of simple HP dryer and solar-assisted HP dryer are found 0.205 and 0.342 kg/kg min, respectively. In another study, Kuan et al. (2019) demonstrated that the HP dryer decreases the initial moisture content of banana from 74% to the final moisture content of 19% in 21 h. Similarly, the conventional solar dryer reduces the initial moisture content from about 74% to the final moisture content of about 20% in 35 h. Drying performance and mathematical modeling of banana slices in a HP dryer system was investigated by Tunçkal and Doymaz (2020). The authors reported that the activation energy ($E_a$) was 51.43 kJ/mol and the color index values of a and C increased, whereas those of L, b and $\Delta E$ indexes reduced as the drying temperature increased.

Grape

Drying kinetics and quality parameters of grape pomace dried with a HP dryer were reported by Taşeri et al. (2018). The authors reported that the application of 2 m/s in pomace drying process with HP method gave better results than other applications in terms of bioactive properties of samples. In addition, energy consumption of grape pomace dried by HP could be decreased by 51% compared with convective dryer. In another study, effects of HP dryer temperatures (45 and 50°C) on bioactive properties and the drying characteristics of grape pomace were reported (Aktaş et al., 2019). It was reported that increasing temperature reduced the drying time, COP of whole system, and specific energy consumption. The results show that drying the grape pomace at low temperature is more suitable for product quality. Also, bioactive properties of dried samples at drying air temperature of 45°C are better than 50°C. Zsivanovits et al. (2013) used HP dryer for drying of red grape. They reported that the dielectric parameters are useful for HP drying process.

Jujube

HP dryer is proven as drying system that ensures the product’s quality especially fruit crops, able to control drying temperature, relative humidity, moisture contain extraction, drying air velocity, and drying period (Goh et al., 2011). The application of HP dryer contributes positively to the following fruit quality attributes including improved microbial safety, better color, vitamin C retention, improved volatile compound, aroma and flavor compounds, rehydration, and textural properties (Fayose and Huan, 2016). The appearance quality ($L^*$ and $\Delta E$ indexes, and shrinkage) improvement of jujube slices during HP drying was studied by Hou et al. (2020). HP system significantly decreased the shrinkage ratio of jujube slices and improved the appearance quality of slices. Also, energy-saving effect of HP drying (21.5%) was very significant compared with hot air drying.

Kiwifruit

Contact ultrasound technology is the use of an ultrasound device that can transmit mechanical waves with wavelength of higher than 20 kHz and achieve the matching of ultrasonic transducer, radiation
plate, and materials. It has been paid more and more attention in strengthening drying process (Liu et al., 2019). Liu et al. (2020) examined the effect of ultrasonic power on water removal kinetics and moisture migration of kiwifruit slices during contact ultrasound intensified HP drying. The results showed that contact ultrasound application reduced the drying time of HP drying significantly, and the increase of ultrasonic power had stronger reinforcing effect on dehydration rate. Also, the scanning electron microscopy results showed that increasing ultrasonic power produced more porous and spacious microstructure which was beneficial for water migration. Effect of air recirculation and HP drying on mass transfer and energy parameters in drying of kiwifruit slices was studied by Mohammadi et al. (2019). The results showed that the air recirculation had significant effect on mass transfer and energy parameters and higher temperature and recirculation rate resulted in higher specific moisture extraction rate. In summary, HP and air recirculation increased drying rate of kiwifruit slices.

**Pineapple**

HP systems offer economical alternatives of recovering heat from different sources for use in various industrial, commercial and residential applications (Chua et al., 2010). Also, HP dryers are an alternative method for drying heat-sensitive food products at low temperature and less relative humidity with lower energy consumption (Pal and Khan, 2008).

Drying kinetics of HP dried pineapple slices was examined by Tunçkal et al. (2018). The authors reported that the $D_{\text{eff}}$ values of pineapple slices were obtained as the range of $3.78 \times 10^{-9}$ to $6.57 \times 10^{-9}$ m$^2$/s. Also, activation energy of pineapple slices was reported as 75.24 kJ/mol.

**Conclusion**

HP technique is a novel and useful drying technique with comparative advantages, such as independent control of the operation parameters (temperature and humidity), higher energy efficiency, higher drying performance and less quality loss, and it is suitable for drying heat-sensitive fruit crops. This technique dehydrates fruits by providing heat to a closed circulation of dry air and it is not affected by outside weather, keeping a stable temperature at anytime during the year and do not produce environmental pollution. Effect of HP drying systems on the $D_{\text{eff}}$ of some fruit crops was reported. The $D_{\text{eff}}$ values lie within in range of $10^{-7}$ to $10^{-11}$ m$^2$/s for some fruit crops during drying by HP dryer. In development of an energy-saving system, system cost, economical factor, system efficiency and performance, system demand and system dependency of fossil fuel is important. Combination of other drying techniques include solar, infrared and vacuum drying and HP dryer has been reported as an efficient and rapid drying method compared to HP drying alone. Also, hybrid more technology might increase the system performance.

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