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Review on low-temperature heat pump drying applications in food industry: Cooling with dehumidification drying method

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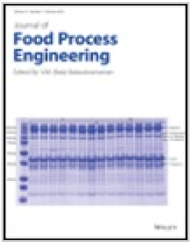

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Review on Cooling with dehumidification drying method

What is it about?

Moisture content of food material is a key factor influencing the quality of storage and extending the quality of a food product. Manufacturers develop new technologies to process sensitive food materials to supply new products with improved properties and high quality. The process in which the air is cooled sensibly while the moisture is removed from food is called cooling with dehumidification process. The system fundamentally acts as a heat pump, which pumps the heat from the dehumidified air to a different air stream in another area, with the aid of a refrigerant gas to carry the heat. This article reviews the potential of low-temperature heat pump dehumidifier drying used in the food industry. Moreover, this describes the principle of cooling with dehumidification (CWD) process, the importance of studying psychrometric charts to understand CWD process, measures used in identify energy efficiency, comparison of this method over common dryers, applications, advantages and limitations of the CWD drying method.

Why is it important?

Multiple measures have been taken to increase the drying efficiency of convection drying, especially by the application of cooling with dehumidified techniques. This drying technique has comparably higher energy efficiency, better and consistent product quality and the ability to control drying temperature and humidity over other conventional methods. Low-temperature heat pump dryers are used increasingly applications in the food industry for the drying of grains, fruits, vegetables, herbs, spices, fish, meat, pet foods, and other heat-sensitive food products in several countries.

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REVIEW ARTICLE

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Review on low-temperature heat pump drying applications in food industry: Cooling with dehumidification drying method

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Abstract

Moisture content of food material is a key factor influencing the quality of storage and extending the quality of a food product. Manufacturers develop new technologies to process sensitive food materials to supply new products with improved properties and high quality. The process in which the air is cooled sensibly while the moisture is removed from food is called cooling with dehumidification process. The system fundamentally acts as a heat pump, which pumps the heat from the dehumidified air to a different air stream in another area, with the aid of a refrigerant gas to carry the heat. This article reviews the potential of low-temperature heat pump dehumidifier drying used in the food industry. Moreover, this describes the principle of cooling with dehumidification (CWD) process, the importance of studying psychrometric charts to understand CWD process, measures used in identify energy efficiency, comparison of this method over common dryers, applications, advantages and limitations of the CWD drying method.

Practical applications

Multiple measures have been taken to increase the drying efficiency of convection drying, especially by the application of cooling with dehumidified techniques. This drying technique has comparably higher energy efficiency, better and consistent product quality and the ability to control drying temperature and humidity over other conventional methods. Low-temperature heat pump dryers are used increasingly applications in the food industry for the drying of grains, fruits, vegetables, herbs, spices, fish, meat, pet foods, and other heat-sensitive food products in several countries.

1 | INTRODUCTION

Drying is a unit operation that has been applied in different industries including food industry since ancient times (Hall, 2007; Hepbasli, Colak, Hancioglu, Icier, & Erbay, 2010). Drying preserves the product by removing some amount of water in the material, while freezing reduces its temperature below the freezing point of water. There are three ways to eliminate moisture from the air: by cooling it to condense water vapor, by increasing the total pressure which leads condensation and passing the air over a desiccant, which pulls moisture from the air through differences in vapor pressures (Dai, Wang, Zhang, & Yu, 2001; Harriman, 2002; Yohana, Endy Yulianto, Bahar, Alifa Muhammad, & Laura Indrayani, 2018). The operation in which the air is cooled sensibly while simultaneously reducing its moisture content is called as cooling and dehumidification process (Harriman, 2002).

A higher amount of energy is required in the food processing to eliminate water from food products. Since drying processes are

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Abbreviations: CWD, cooling with dehumidification; COP, coefficient of performance; COP_A, actual coefficient of performance; CFC, *chlorofluorocarbon*; HP, heat pump; HPD, heat pump dehumidifier; HCFC, hydrochlorofluorocarbon; HFC, hydrofluorocarbons; SMER, specific moisture extraction rate; SEC, specific energy consumption; h_{fg}, heat of evaporation (J/kgK).

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energy-intensive, knowledge about their efficiency and optimum operating conditions is vital for the economical operation of dryers (Chua, Mujumdar, Hawlader, Chou, & Ho, 2001; Colak & Hepbasli, 2009; Ogura et al., 2005; Perera & Rahman, 1997). Drying makes use of single or a combination of convection, conduction, or radiation to conduct heat to the product that is to be dried. Multiple measures have been done to increase the drying efficiency of convection drying (Colak & Hepbasli, 2009; Eisa, 1996), particularly by the application of cooling with dehumidifying. Low-temperature heat pump dehumidifier (HPD) dryers are finding increasing applications in the food industry for the drying of grains, fruits, vegetables, herbs, fish, meat, and other food products in different countries.

Immediately once the air is chilled beneath its dew point temperature the moisture condenses on the nearest surface. Accordingly, the air is dehumidified by cooling and condensation processes. The quantity of moisture eliminated depends on how cold the air can be chilled and when temperature is lower it dries more air (Harriman, 2002). Immediately upon the air at a given dry bulb temperature is cooled lower than its dew point temperature, cooling and dehumidification process is accomplished. This process undergoes in most residential and commercial air conditioning systems (Daghigh, Ruslan, Sulaiman, & Sopian, 2010). A refrigeration system cools air and drains away some of its moisture as condensate and sends air to the cooler, dries air back to space. The system basically pumps the heat from the dehumidified air to another air stream in different location, using the coolant (refrigerant gas) to carry the heat. Dehumidification through air cooling can be illustrated on a psychrometric chart for atmospheric pressure.

This article reviews the potential of cooling with dehumidification (CWD) drying to be used especially in the food industry. Moreover, this article describes how CWD processes are achieved and how they are represented on the psychrometric chart, principles of cooling with dehumidifying drying method or the HPD drying, performance evaluating measures, general comparison over other common dryers, food applications, advantages, and limitations of CWD. These review findings will be beneficial for both food manufacturers and researches who will carry out future studies related to the field of dehydration technology and especially, CWD drying.

2 | LOW-TEMPERATURE HEAT PUMP DRYING METHODS

Heat pump (HP) drying systems have been researched and developed for a long time to improve their performance (Goh, Othman, Mat, Ruslan, & Sopian, 2011). It can be done either in lower (−20°C to 45°C) or higher (45°C to +110°C) temperatures (Figure 1). Solar, microwave, infrared, and radio frequency HP systems require higher temperatures while chemical, vacuum and cooling with dehumidified HP systems operate at relatively low temperatures (Artnaseaw, Theerakulpisut, & Benjapiyaporn, 2010; Goh et al., 2011; Yadav et al., 2016; Yohana et al., 2018). Cooling with dehumidifier HP can be assisted with solar power, coulomb force, single or dual stage heat pumps, and so on (Goh et al., 2011; Minea, 2015). The main advantages of HP technology are the energy saving potential and capability to control drying temperature and air humidity (Chin, Lee, & Chung, 2018; Jangam & Mujumdar, 2011; Minea, 2015; Patel & Kar, 2012). HP system basically pumps the heat from the dehumidified air to a different airstream in another location, using the refrigerant gas to carry the heat (Wang, 2000). In this review article only the dehumidification process is discussed which occurs at lower temperature; that is called CWD process.

The process that the water vapor (humidity) is removed from the air whilst keeping constant dry bulb (DB) temperature is termed as the dehumidification (Harriman, 2002; Sayegh, Hammad, & Faraa, 2011). This process is represented by a straight vertical line on the psychrometric chart (Figure 3a) starting from the initial value of relative humidity, extending downward and ending at the final value of the relative humidity. In actual practice, the pure dehumidification process is not possible, since the dehumidification is always accompanied by cooling or heating of the air (Henning, Motta, & Mugnier, 2013). Dehumidification process together with cooling or heating is used in various air conditioning applications. The cooling and dehumidification of air for human comfort is commonly called air conditioning (Chua, Bui, Kum Ja, Islam, & Oh, 2017).

When the air comes into contact with the cooling coil that is maintained at a lower temperature than its dew point, its DB temperature starts decreasing. The process of cooling continues and at a

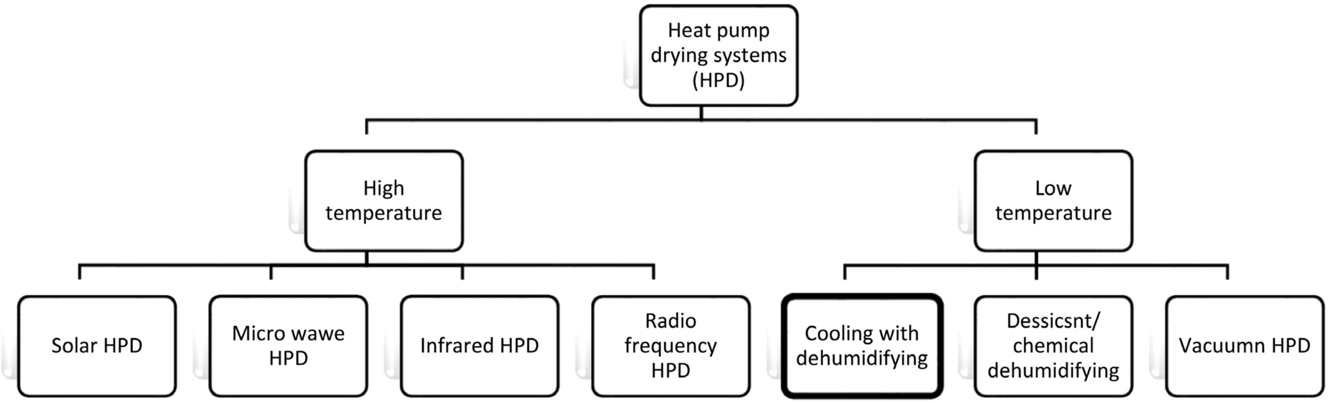

FIGURE 1 Classification of heat pump drying systems based on the temperature applied

certain point it reaches dew point temperature of the air (Harriman, 2002). At this temperature, the water vapor within the air starts getting converted into dew particles, due to which the dew is formed on the surface of the cooling and the moisture content of the air declines thereby reducing its humidity level (Kreith, Wang, & Norton, 1999; Wang, 2000). Accordingly, there is cooling and dehumidification of air when the air is chilled beneath its dew point temperature (Harriman, 2002).

The cooling and dehumidification process is widely used in air conditioning applications (Chua et al., 2017). It is used in all types of air conditioning systems (window, split, packaged and central) to generate the comfort conditions inside the space to be cooled (Khemani, 2010). The evaporator coil is maintained at lower temperature than the atmospheric dew point temperature by the cool refrigerant passing through it in the split air and window conditioners. There are multiple numbers of refrigerants used in HPs such as chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), hydrofluorocarbon (HFC), and natural gases. Carbon dioxide (R744) is a commonly used natural refrigerant applied in food processing due to its eco-friendliness, volumetric capacity, heat transfer properties, and heating capability at higher temperatures (Jangam & Mujumdar, 2011; Kim, Pettersen, & Bullard, 2004; Sarkar, Bhattacharyya, & Ramgopal, 2004). In cooling, refrigeration and drying horticultural products distribution and flow rate of the air are the critical factors to be concerned (O'Sullivan et al., 2014). When the room air/atmospheric air moves over evaporator coil its DB temperature reduces and simultaneously moisture is also removed since the air is cooled below its dew point temperature. The dew formed on the cooling coil is evacuated out by small tubing. The cooling coil is cooled by the refrigerant or the chilled water in central air conditioning systems (Khemani, 2010). Meanwhile, the atmospheric air passes over this coil, it gets cooled and dehumidified. Basically the cooling and dehumidification process is occurred by passing the air over coil through which the cool refrigerant (cooled gas) is passed (Harriman, 2002).

Throughout the CWD process, the dry bulb, the wet bulb, and the dew point temperature of air declines. Furthermore, the sensible heat and the latent heat of the air reduce causing all over reduction in the enthalpy of the air. The CWD process is represented by a straight angular line on the psychrometric chart (Figure 3b). The line begins from the given value of the dry bulb temperature and moves downward toward left.

3 | PSYCHROMETRIC CHART

Psychrometric chart was developed by a German engineer, Richard Mollier in the early 1900s (Todorovic, 2014). This is a graph (Figure 2) that represents the properties of moist air from the point of view of the dry bulb, wet-bulb temperature, relative humidity, humidity ratio, and enthalpy. Three of these properties are sufficient to define the status of moist air. It is important that the chart can be used only for the atmospheric pressure (i.e., 1 atm, or 101.3 kPa). If the atmospheric pressure varies, different humid air equations can be used.

Understanding the dynamics of air humidity will provide foundation for understanding the principles of the refrigeration and air conditioning systems. Figure 3 shows multiple processes on the psychrometric chart. Figure 3a exhibits an example of dehumidification on a constant DB temperature with the decrease of humidity ratio. Figure 3b shows both the cooling and dehumidification process of the air, which led to a decline in both dry bulb and wet-bulb temperature and humidity ratio. This chart indicates both sensible and latent heat removes as condition moves toward left on the chart. In

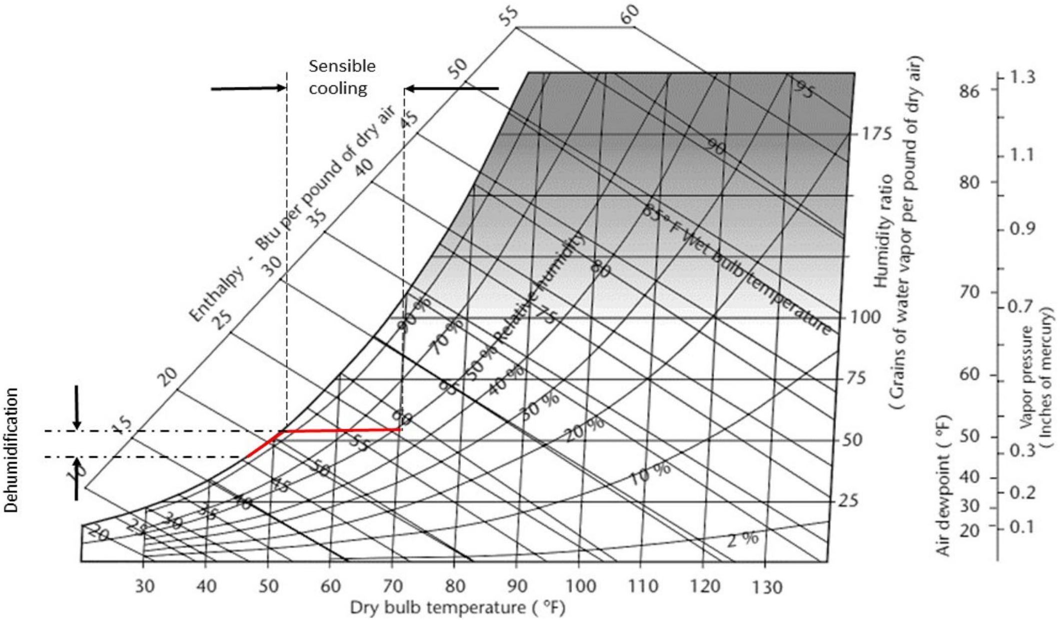

FIGURE 2 Dehumidified air path on the psychrometric chart

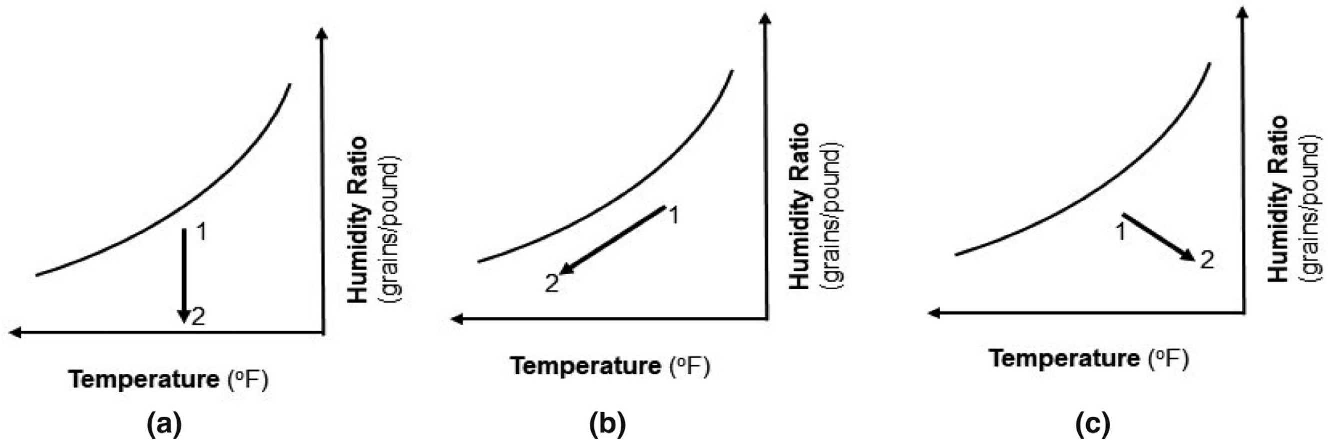

FIGURE 3 Dehumidification process on the psychrometric chart. (a) dehumidification at constant dry bulb temperature. (b) Cooling with dehumidification process of air. (c) Chemical dehumidification process of air

this situation, both moisture and heat are removed from the air. Figure 3c exhibits chemical dehumidification process, where water vapor is absorbed or adsorbed from the air using an absorbent material.

Cooling systems first chill the air to its dew point (100% relative humidity). After that point, further chilling removes moisture. The more the air is cooled, the deeper air will be dried (Harriman, 2002).

Cooling with dehumidifying process can be further understood by studying psychrometric chart. As an example from Figure 1; if air is cooled from 70 °F to 51 °F (horizontal red line), no moisture is removed from the system. But when the air is at 51 °F, it is saturated (100% relative humidity). If it is further cooled, moisture will be condensed out of the air. If the air is cooled from 51 °F to 45 °F (straight angular red line), 11 grains of moisture will be removed through the condensation while dehumidifying the air (Harriman, 2002).

4 | PRINCIPLE OF COOLING WITH DEHUMIDIFY DRYING METHOD

The dehumidifier is an air-to-air low temperature heat pump that functions in a way similar to the domestic refrigerator; it consists of a condenser (hot heat exchanger), a compressor, and an evaporator (cold heat exchanger).

Figure 4 depicts a schematic layout of a heat pump drying system or cooling with dehumidifying drying system. There are basically two systems in a heat pump, as refrigerant pathway and air pathway (Daghigh et al., 2010; Harriman, 2002). In the inside loop, it represents the pathway of refrigerant and outside loop represents pathway of the air. The refrigerant at the evaporator undergoes phase changes from liquid to vapor by absorbing heat of the air. Then the vaporized refrigerant goes to the pump where the pressure is increased and further passed into the condenser. In the condenser, the refrigerant changes its phase from vapor to liquid by releasing latent heat (Daghigh et al., 2010; Yaqub & Zubair, 2001). Then, the liquidized refrigerant flows to an expansion valve and directly goes to the evaporator.

As stated previously, refrigerant changes into vaporous state from the liquid state at the evaporator whereby absorbing the heat of moisture-laden air which comes from the dryer (Figure 5a) component (Daghigh et al., 2010; Goh et al., 2011; Sagar & Suresh Kumar, 2010). Consequently, air gets cooled and dehumidified in the evaporator. In this process, air is first cooled sensibly to its dew point temperature and further cooling at the dew point produces water by condensation of air at the evaporator surface. When moisture-laden air passed through the evaporator, it becomes dehumidified cold air. The RH of this dehumidified air assumed to reach 100%, while the temperature of the condensate water assumed to be the temperature of the dehumidified cold air at the evaporator outlet (Yuan et al., 2019). Then remained air flows to the condenser where refrigerant condenses and removes heat. This heat is absorbed by the cold air and it becomes dry air prior going to the dryer. The dryer is where the food item or the material placed inside. Hot air comes toward the dryer and it moves away from the dryer by absorbing moisture from the food item to the evaporator. This process continuously occurs and ultimately the food item get dehydrated (Daghigh et al., 2010; Harriman, 2002).

The actual hardware that accomplishes cooling dehumidification is exceptionally diverse. Generally many number of different combinations of compressors, evaporators and condensers are in use throughout the world. However, there are three basic equipment configurations of interest to design humidity control systems, which include direct expansion cooling, chilled liquid cooling and dehumidification with reheat (Harriman, 2002).

Heat is removed from the dehumidified air by first transferring its thermal energy to a refrigerant which is inside the cooling coil that chilled the air. The coil is called the evaporator, because the refrigerant is evaporating inside the coil and expanding from a liquid to a gas (Figure 5b). This expansion occurs inside the coil by absorbing heat from the air passing through the coil.

From the cooling coil, the refrigerant gas is sent to a compressor, where its pressure is increased considerably about 5–10 times greater than when it left the evaporator coil (Harriman, 2002). The gas is therefore a much smaller volume, but compression has raised its

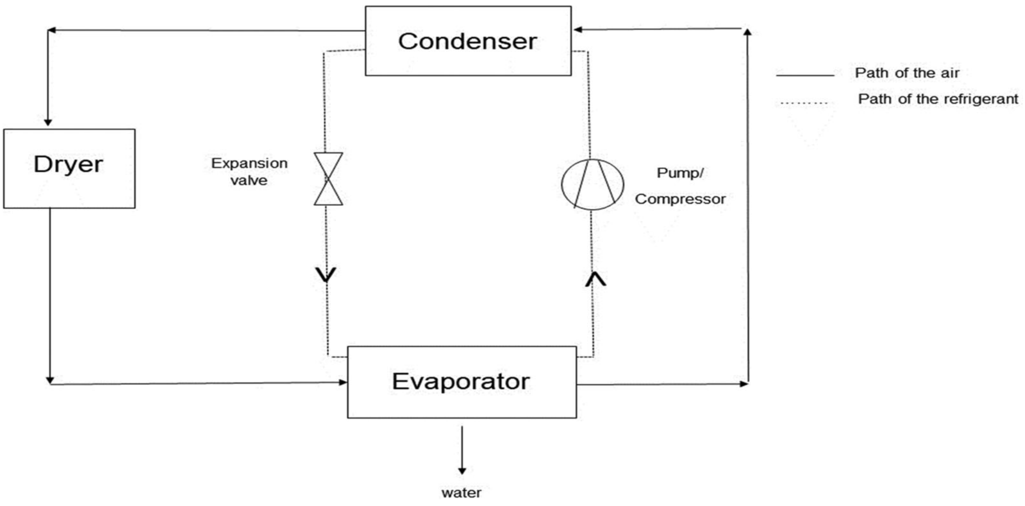

FIGURE 4 Schematic diagram of cooling with dehumidification drying system

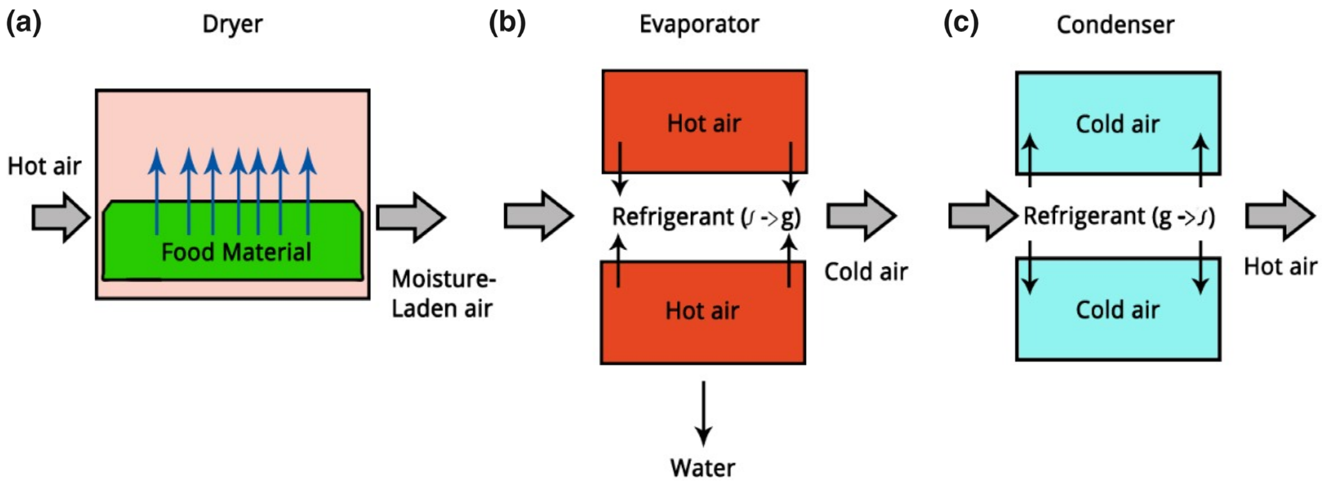

FIGURE 5 Major components used in cooling with dehumidification drying process (a) dryer, (b) evaporator, (c) condenser

temperature. For instance, the gas may have been at 60 °F after it absorbed the heat from the air on the other side of the evaporator coil. Although after compression, the refrigerant gas may be nearly 200 °F (93°C). That heat from the process of compression itself is removed from the refrigerant. This is accomplished by running the gas through a condenser (Harriman, 2002).

The condenser is located outside the conditioned space, in a place where the heat can be rejected to the air without causing problems. In air conditioning systems condenser units are often located outside a building or on a rooftop (Wang, 2000). The compressed, hot refrigerant condenses back to a liquid inside the coil, while heat is transferred to the air on the other side of the condenser coil (Figure 5c). The cooled refrigerant liquid then return to the coil cooling the earliest airstream. As the liquid expands again back to a gas inside the evaporator coil, the cycle repeats while absorbing more heat (Figure 4; inside loop).

The process can be very efficient. The ordinary measure of efficiency is the coefficient of performance, which is the energy removed from the dehumidified airstream divided by the energy invested to accomplish the transfer to the condenser airstream (Fayose & Huan, 2016; Wang, 2000). This transfer energy consists of the compressor energy plus the fan energy that pushes air through the two coils. Many electrically driven refrigeration systems have coefficients of performance of 2.0–4.5 (Lychnos & Tamainot-Telto, 2018; Wang, 2000). It implies the system moves two to four and a half times as much thermal energy as it consumes in electrical energy. It is considered as a very favorable ratio of performance.

5 | ENERGY EFFICIENCY AND OTHER MEASURES OF HPD

Drying is one of the most energy intensive unit operation that accounts utilization of nearly 15% of all industrial energy (Chua et al., 2001; Goh et al., 2011; Hepbasli et al., 2010; Raghavan et al., 2005). Drying efficiency is a measure of quantity of energy used in removing a unit mass of water from a product. HPDs are an alternative technique for drying products at lower temperature with lower energy consumption and less relative humidity (Teeboonma, Tiansuwan, & Soponronnarit, 2003; Vázquez, Chenlo, Moreira, & Cruz, 1997). The energy efficiency of a heat pump is defined by the coefficient of performance (COP), which is the energy removed from the dehumidified airstream divided by the energy invested to accomplish the transfer to the condenser airstream (Eisa, 1996; Harriman, 2002; Queiroz, Gabas, & Telis, 2004; Wang, Brown, & Cleland, 2018). This transfer energy comprised of the compressor energy and the fan energy that pushes air through the two coils. COP is given by,

$$\mathrm{COP} = \frac{\text{useful heat output}}{\text{power input}} \tag{1}$$

The maximum theoretical heat pump efficiency is given by the Carnot efficiency as,

$$\mathrm{COP}_{\mathrm{carnot}} = \frac{T\,\text{condenser}}{T\,\text{condenser} - T\,\text{evaporator}} \tag{2}$$

The $\mathrm{COP}_{\mathrm{carnot}}$ cannot be realized physically, but it is used as a gauge to determine how far a refrigeration system is from the ideal system. Usually, these temperatures are measured at the inlet and outlets of each component for assessing and monitoring the heat pump performance. When measuring these temperatures thermometer probes should contact the refrigerant fluid flowing inside the tubing. These sensors may be inbuilt or separate. Pressure values are typically measured by the pressure gauges attached to the tubing, at inlets and outlets of the components.

In practice, the actual efficiency of the heat pump is usually 40–50% of the theoretical Carnot efficiency (Chua, Chou, Ho, & Hawlader, 2002; Prasad, 2011). Cascade HP has been developed to increase COP values of HPD (Boahen & Choi, 2017; Dinçer & Kanoğlu, 2010). Another performance indicator that is generally used to define the performance of dryer is the specific moisture extraction rate (SMER). SMER is defined as,

$$\mathrm{SMER} = \frac{\text{amount of water evaporated}}{\text{energy input to the dryer}} \tag{3}$$

Units of the SMER are expressed as the ratio of the moisture removed (kg) to the energy input as above (Ahmed & Rahman, 2012). SMER for a particular HP varies depending on many factors including the type of utilized working fluid (refrigerant) and air drying temperature. Another parameter known as the specific energy consumption (SEC), which is the reciprocal of the SMER, can be used to compare energy efficiencies of different types of dryer (Baysal et al., 2015). The SEC can be given by,

$$\mathrm{SEC} = \frac{\text{Heat pump power consumption (kW)}}{\text{Dehumidification rate (kg water/s)}} \tag{4}$$

The SMER values of HP dryers have been found to be dependent on the maximum air temperature, humidity, the operating temperature of evaporator and condenser and the overall efficiency of the HP cycle. As a rule of thumb, as the COP of the HP cycle increases the SMER value raises too (Chua et al., 2002).

The relation between SMER and COP, neglecting sensible heat in water extracted, is given as,

$$\mathrm{SMER} = \frac{\mathrm{COP_A} - 1}{h_{\mathrm{fg}}} \tag{5}$$

where actual coefficient of performance is denoted by $(\mathrm{COP})_{\mathrm{A}}$ and heat of evaporation (J/kgK) is denoted by h_{fg} (Ahmed & Rahman, 2012; Zlatanović, Komatina, & Antonijević, 2017). Moreover, researchers have evaluated and conferred step-wise design procedures for HP dryer components with mathematical models that can be adopted within certain limitations and assumptions (Pal & Khan, 2008).

6 | GENERAL COMPARISON WITH OTHER COMMON DRYERS

The drying is a complex operation that involves mass and heat transfer along with physical and structural variations (Senadeera, Alves-Filho, & Eikevik, 2013). SMER is a commonly used indicator to evaluate performance of a drier. Although the main objective of food drying is preservation, it is affected by the drying method ultimately ending up raw material in to a completely different material with significant variation in product quality (Chou & Chua, 2001).

Among the methods stated in Table 1, low-temperature HPD is having higher SMER range (0.3–5.0) over other methods. As the COP of the HP cycle increases the SMER value of the HP dryer increases too. Therefore, among those methods low-temperature HPD is a more efficient method. It is apparent both low-temperature HPD and freeze-drying methods which cover lower temperature ranges ultimately leads to have higher quality products in aspects of preserved nutrition, color, aroma, flavor, and so on.

Low energy efficiency and longer drying duration are the main disadvantages of convective drying caused by poor thermal conductivity to the inner sections of the material (Pan, Shih, McHugh, & Hirschberg, 2008). Even though HP has moderate initial cost, running cost is comparably lower to other conventional drying methods (Wang, Zhang, Han, Zhang, & Tian, 2011; Zhang et al., 2017). HP dryers are known to be cost effective in many drying applications because it can extract and utilize the latent energy of the air and water vapor for drying product (Wang, 2000). It has been established that HP drying consumes only about half or one-third of the electricity of conventional condenser dryers. However, researchers have (Prasertsan & Saen-saby, 1998; Raghavan et al., 2005) revealed that HPD had the lowest operating cost when compared to electrically heat convective dryers (Patel & Kar, 2012). For heat pump dryers, the total cost of eliminating a liter of water from a product was observed

TABLE 1 General Comparison of low temperature HPD with other common dryers

	Low-temperature HPD	Hot air drying	Vacuum drying	Freeze drying	Sun drying
SMER (kg/kWh)	0.3–5.0	0.1–1.3	0.7–1.2	0.4 or lower	0.84
Operating temperature (°C)	−20 to 40	40 to very high	30 to 60	−35 to 50	30 or high
Operating RH%	10–50	Variable	Low	Low	Less than 60
Drying efficiency%	Up to 95	35–40	Up to 70	Very low	20–30
Drying rate	Faster	Average	Very slow	Very slow	Slow
Product quality	Very good	Average	Good	Excellent	Average
Rehydration properties	Very good	Average	Moderate	Good	Poor
Capital cost	Moderate	Low	High	Very high	Low
Running cost	Low	High	Very high	Very high	Low
Control	Very good	Moderate	Good	Good	Low

Note: Sources: Fayose and Huan (2016); Huang, Zhang, Mujumdar, and Lim (2011); Jangam and Mujumdar (2011); Krokida and Philippopoulos (2005); Mohanraj and Chandrasekar (2009); Perera and Rahman (1997).
Abbreviations: HPD, heat pump dehumidifier; SMER, specific moisture extraction rate; RH, relative humidity.

considerably lower at for long hours than at short hours of operation. Sosle and others (Sosle, Raghavan, & Kittler, 2003) revealed that HPD is useful for materials with high initial moisture content and in regions with high humidity of ambient air.

Moreover, among the other numerous observations about HP drying that worth future study is the use of the clean water, which is gained by condensation. According to current concerns, the water might be used as a side product. Finally, the heat pump can also be used as cooling plants, which could be a basis for further developments toward the cooling and storing of fruit (Fayose & Huan, 2016). Zhou and others have stated that moisture reduction rate of HDP is more unique than other methods (Zhou et al., 2018). Preliminary studies found that the color and aroma qualities of dried agricultural products using heat pumps were better than those products using conventional hot air dryers (Prasertsan & Saen-saby, 1998; Soponronnarit, Wetchacama, Swasdisevi, & Chotijukdikuld, 1999; Teeboonma et al., 2003; Uddin, Hawlader, & Hui, 2004). Moreover, the researcher Sosle (2002) had revealed that apple samples which had been subjected to HP dehumidifier drying showed better rehydration properties, color preservation, lower water activity, and less cellular structure damages over hot air dried (45–65°C) samples (Sosle, 2002).

High drying temperature usually causes quality degradations in food products, especially hot air drying (Arabhosseini, Padhye, Huisman, van Boxtel, & Müller, 2011; Swasdisevi, Devahastin, Sa-Adchom, & Soponronnarit, 2009). Generally, food products lose aroma and nutritional content when exposed to a higher temperature for a longer period to achieve a particular dried product. HPs retain those volatile compounds as the system operates in a closed system (Bengtsson, Berghel, & Renström, 2014). Any volatile compound eliminated during drying can be retained through HP. Heat pump dryer can be considered as an alternative method for drying products with lower energy consumption, less relative humidity and lower temperature (Bengtsson et al., 2014; Chin et al., 2018; Sagar & Suresh Kumar, 2010; Sahoo, 2012).

7 | APPLICATIONS IN THE FOOD INDUSTRY

Applications on heat pumps for drying in industrial scale have been implemented for many years (Goh et al., 2011; Patel & Kar, 2012). As listed in Table 2, several applications of low-temperature HPD (CWD) have been reported in the food industry in different regions of the world. In past recent decades, this technique has been applied for grains, fruits, vegetables, herbs, seafood, dairy products, pet foods, and so on (Alves-Filho et al., 2007). Food products with higher moisture content can be dried effectively with HP drying. As drying air absorbs more of this available energy, the latent energy can be transferred at the evaporators for higher heat recovery.

Jinjiang and Yaosen have found that low temperature HP drying of paddy could save energy and increase the quality of final products over other selected conventional methods (Jinjiang & Yaosen, 2010). Researchers have shown that heat pump dehumidified drying proceeded for ginger using two stage drying can reduce the drying time at 40°C by 59.32% with increase of 6-gingerol content by 6% (Phoungchandang & Saentaweesuk, 2011). Hawlader and others have found that effective diffusivity during the drying process can be improved by using HPs with a modified atmosphere (CO_2) for drying guava and papaya, compared over vacuum and freeze dryers (Hawlader, Perera, & Tian, 2006; Hawlader, Perera, Tian, & Yeo, 2006). HPD had been applied for banana drying in Thailand at 30–40°C and they have achieved SMER value of 0.540 kg/kWh with better sensory properties (Prasertsan & Saen-saby, 1998). Chong and others have found that microwave assisted HP drying preserved the highest amount of total polyphenol content, antioxidant activity and the best appearance quality of apple dices compared over other drying methods (Chong et al., 2014). Additionally, results of the dried green sweet pepper (Pal et al., 2008) using HPD at 30–40°C, preserved chlorophyll and ascorbic acid because of the lower drying temperatures used. Costa and others (Costa et al., 2016) have found that the drying operation of microalgae using a heat pump (30–50°C) can

TABLE 2 Various applications of low-temperature HPD on different food items

Application	Item	Temperature applied (°C)	Location	References
Grains and minor crops	Green sweet pepper	35	Thailand	Goh et al. (2011)
	Green sweet pepper	30 to 40	India	Pal, Khan, and Mohanty (2008)
	Red pepper	−3 to 20	Thailand	Prasertsan and Saen-saby (1998)
	Red pepper	−3 to 20	Norway	Alves-Filho, Eikevik, Mulet, Garau, and Rossello (2007)
	Rice	30.8	Mexico	Best, Cruz, Gutierrez, and Soto (1996)
	Paddy	23 to 33	China	Jinjiang and Yaosen (2010)
	Special crop	30 to 45	Canada	Adapa, Schoenau, and Sokhansanj (2002)
Fruit	Apple	39 to 41	Turkey	Aktaş, Ceylan, and Yilmaz, (2009)
	Apple	35	Malaysia	Chong, Figiel, Law, and Wojdyło (2014)
	Apple	45	Canada	Sosle (2002)
	Apple wax coating	32 to 34	USA	Norris and Ave (1986)
	Banana	30 to 35	Australia	Dandamrongrak, Young, and Mason (2002)
	Banana	30 to 40	Thailand	Prasertsan and Saen-saby (1998)
	Banana	30 to 35	Singapore	Chua et al. (2001)
	Banana	40 to 50	India	Singh, Sarkar, and Sahoo (2020)
	Guava	30	Australia	Dandamrongrak et al. (2002)
	Nectarine	25	Australia	Sunthonvit, Srzednicki, and Craske (2007))
	Pears	20 to 30	Australia	Dandamrongrak et al. (2002)
	Pineapple	37 to 43	Turkey	Tunçkal, Coşkun, and Doymaz (2018)
	Guava and papaya	45	Singapore	Hawlader, Perera, and Tian (2006) and Hawlader, Perera, Tian, and Yeo (2006)
Herbs and vegetables	Bay leaves	40	Turkey	Kuzgunkaya and Hepbasli (2007)
	Ginger	40	Thailand	Phoungchandang, Nongsang, and Sanchai (2009) and Phoungchandang and Saentaweesuk (2011)
	Potato	40 to 50	India	Singh et al. (2020)
	Kaffir lime leaves	0 to 50	Thailand	Phoungchandang, Srinukroh, and Leenanon (2008)
	Japanese honeysuckle (flower buds)	40	China	Liu, Miao, Wu, and Liu (2014))
	Sweet basil leaves	40	Thailand	Phoungchandang and Kongpim (2012)
	Olive leaves	40 to 51	Turkey	Erbay and Icier (2009)
	Mint leaves	35–37	India	Venkatachalam, Thottipalayam Vellingri, and Selvaraj (2020)
	Moringa leaves	40 to 50	Thailand	Potisate, Phoungchandang, and Kerr (2014)
Seafood	Mackerel	20 to 30	China	Shi, Xue, Zhao, Li, and Wang (2008)
	Tilapia fish fillets	5 to35	China and UK	Li, Wu, Ge, and Ling (2019))
	Cod fish	−5 to 45	Australia	Minea (2015) and Strommen (1999)
Dairy	Cheese	0 to 12	Spain	Castell-Palou and Simal (2011)
Other	Granular food	−20 to 40	Norway	Ingvald Str⊘mmen and Kramer (1994)
	Alfalfa	25 to 45	Canada	Adapa et al. (2002)
	Blue-green algae (*Spirulina sp.*)	30 to 50	Brazil	Costa et al. (2016)
	Cabbage seeds	40	China	Yang, Zhu, Zhu, Wang, and Li (2013)
	Hawthorn cakes	45	China	Wang et al. (2011)
	Konjac flour films	30 to 50	Thailand	Jomlapeeratikul, Poomsa-Ad, and Wiset (2017)
	Mushrooms	45	Turkey	Şevik, Aktaş, Doğan, and Koçak (2013)
	Instant food (cranberry and potato)	−10 to 30	Norway	Alves-Filho (2002)
Pet food	Bovine intestine	−10 to 25	Norway	Senadeera et al. (2013)

retain bioactive compounds (phyco-cyanin) in the dried product (nutritional supplement) because of the regulated conditions (temperature and humidity). Most recent research studies on drying mint leaves through low-temperature (30–37°C) had shown that this method had retained the ascorbic acid content in the dried product (Venkatachalam et al., 2020). Moringa (*M. olifera*) leaves which are higher in nutrients and phytochemicals have been dried using a heat pump dryer at 40–50°C (Potisate et al., 2014; Rathnayake, Navaratne, & Uthpala, 2019). Potisate and others have found that heat pump drying at 50°C provides a better quality dried moringa leaves with higher quercetin and kaempferol levels compared with hot air drying and microwave drying (Potisate et al., 2014).

HP drying applications on red pepper, green sweet pepper, ginger, kaffir lime leaves, sweet basil leaves and Konjac flour films have been reported in Thailand and India while guava, banana, nectarine and cod fish were reported in Australia. In Turkey, this technique was applied to dry apples, pineapples, mushrooms bay leaves and olive leaves while it has applied to dry paddy, cabbage seeds and mackerel in China. Moreover, researches have observed that heat pump drying is an efficient, eco-friendly method to obtain high-quality pet food products (bovine intestine) at a lower cost (Senadeera et al., 2013).

8 | ADVANTAGES OF CWD DRYING

The final intention of drying in the food industry can be categorized into three aspects, such as economic concerns, environmental considerations, and quality of the product (Fayose & Huan, 2016; Zhang et al., 2017). Cooling with dehumidify dryers provide multiple advantages over typical conventional hot-air dryers for the drying of food products, covering higher energy efficiency, better product quality and the ability to work independently of outside ambient weather conditions (Daghigh et al., 2010; Perera & Rahman, 1997; Prasertsan & Saen-saby, 1998; Sosle et al., 2003; Yahya, Fudholi, Hafizh, & Sopian, 2016). The greatest advantage of HPD in food drying is, its ability to utilize the low-grade heat in moisture-laden (humid) air for efficient work (Jangam & Mujumdar, 2011).

Warm and humid air is a barrier in hot air convective drying operations. Nevertheless, warm and humid air provides an unlimited source of heat for the HPD and creates an ideal environment for drying. Through heating of the dehumidified air, the recovered heat is recycled back to the dryer. The energy efficiency increased substantially as a consequence of heat recovery (Fayose & Huan, 2016; Jangam & Mujumdar, 2011). Due to the improvement of energy efficiency and less fossil fuel consumption, HD drying can be considered as a sustainable method (Colak & Hepbasli, 2009). The main advantages are the energy-saving potential and capability to control drying temperature, flow rate and air humidity leading to better quality food products (Donghai & Sheng, 2001; Jangam & Mujumdar, 2011; Prasertsan & Saen-saby, 1998; Sarkar et al., 2004).

Additionally, this technology is eco-friendly therein gases and fumes are not given off into the atmosphere. The condensate can be regained and eliminated. Moreover, there is a potential to recover valuable volatiles from the condensate. For the high moisture containing food materials, lower temperature heat pump drying is an efficient dehydration method (Sun et al., 2017). Also better quality (Sagar & Suresh Kumar, 2010), consistent products can be achieved due to controlled temperature (up to 50°C) and RH (10–90%) profiles used in cooling with dehumidifying technique. Since HP dryer supplies low relative humidity and low-temperature, researchers have found that HP can reduce the drying time comparable to hot air drying in the Konjac flour film making process (Jomlapeeratikul et al., 2017). The optimum drying temperature for specialty crops includes fruits and vegetables lie between 30 and 45°C, where no structural damage and nutrient losses occur (Adapa et al., 2002; Pal & Khan, 2008). A wide range of drying conditions typically from −20 to 50°C is feasible in CWD drying. The low temperatures applied, as well as the possibility of using an inert atmosphere in HPs, can result in better quality products in aspects of aroma, texture, taste, and appearance (Jangam & Mujumdar, 2011). Hence, heat-sensitive phytochemicals and nutrients can be preserved by applying this drying technique (Ng et al., 2018; Sagar & Suresh Kumar, 2010). Since this HP drying carries in lower temperature auxiliary heating is not required as for the critical pressure level of some refrigerants.

Even though there is some concern about the potential of microbial growth at the lower temperatures used in HPD dryers; in practice, there have not been any reports of increased numbers of microorganisms in dried foods compared over conventional means. Also closed cycle is available in HP causing firmly controlled sanitary conditions in the food drying process (Wang et al., 2011). Also, Chou and others have mentioned that the low energy consumption characteristics (Chou, Chua, Ho, & Ooi, 2004) as well as the capability to aseptic processing of HPs. But, critical microbiological issues may arise if the dryer is poorly designed. For instance, if the refrigeration capacity of the refrigeration circuit is insufficient to condense the moisture in the air, it will lead to high humidity. Under normal circumstances, the rate of vaporization of moisture from the food and the rate of condensation of moisture from the air will be managed to maintain water activity at the surface below the critical value of 0.6, by avoiding microbial growth (Perera & Rahman, 1997).

The HP has expanded to become a mature technology over the past decades and gas engine driven HP and electric driven HPs are available. Gas driven is a natural choice in cooling and heating applications as they improve the overall energy utilization efficiency and reduce the operating cost than electrically driven HPs (Gungor, Erbay, & Hepbasli, 2011).

Furthermore, studies have found that better color and aroma profile, better rehydration properties, lower water activity and lesser degree of cellular structure damage of this heat pump dried agricultural products were observed than those of conventional hot air dryers (Daghigh et al., 2010; Hawlader, Perera, Tian, & Yeo, 2006; Prasertsan & Saen-saby, 1998; Soponronnarit et al., 1999; Sosle, 2002; Strømmen, Eikevik, Alves-Filho, Syverud, & Jonassen, 2002; Zhang et al., 2017).

9 | LIMITATION

Disregard the current food applications CWD drying has to make a significant impact on other food items. There are some issues with this application. Particularly, the initial capital cost may be quite high due to the maintenance of refrigerant components and procurement of various components such as compressor heat exchanger and controllers (Chua et al., 2002; Jangam & Mujumdar, 2011). Compared to other drying methods (solar, oven drying), the initial cost may be higher. But the ability of HPs to recover that heat translates to lower operating cost. Also, this method requires regular maintenance of HP components (compressor, refrigerant filters, heat exchanges, etc.). Refrigerant would leak to the environment if cracking of pipes occurs due to pressurized systems (Jangam & Mujumdar, 2011). If a leak occurs pressure of the HP cycles drops and performance will be diminished. Moreover, environmental issues may be prevailing due to the use of CFC like refrigerants which helps for ozone layer depletion (Jangam & Mujumdar, 2011). However, there are eco-friendly refrigerants such as HCFCs (R22, R124), HFCs (R134a, R152a, R404a) and even natural gases such as carbon dioxide (R744) and ammonia (R717) (Daghigh et al., 2010; Sarkar et al., 2004).

10 | CONCLUSION

There has been an emerging interest in recent decades, to apply low-temperature heat pump (CWD) drying technologies in the food industry due to, well-controlled drying conditions (humidity, flow rate, and temperature). Heat pump drying has the most prominent impact as it recovers a significant extent of energy that unless in vain. Nevertheless, there is a huge potential for research and development in this field. The main restrictions in HPD are quite high capital cost and still the use of conventional eco-unfriend refrigerants in the refrigeration cycle.

Researchers have found that CWD drying offers food products with better quality due to the controlled atmosphere with reduced energy consumption, even though it requires significant capital cost. Also, high-value heat-sensitive food products can be dehydrated through this drying method while preserving nutrition and phytochemicals, improving rehydration (lesser cellular structure damage) and organoleptic (odor, flavor, taste, texture and appearance) properties and further ensuring consumer attractiveness. Therefore, CWD drying is an alternative drying method for drying food products leading to better quality with low cost, safer operation, and higher energy efficiency.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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