Review article

Heat Pump drying of Food Product: A Review

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Abstract: To extend the shelf life of fruits and vegetables, drying is a viable option, but it has its own difficulties. It preserves the fruits and vegetable by reducing the moisture content. The heat pump drying in one of the methods of drying which retains the nutritional component in the dried product as compare to the conventional methods. The major component of heat pump dryer is compressor. The low energy consumption is the main advantage of heat pump dryer. It can be used for heat sensitive product as can dry the product at low temperature as compare to the other conventional method. It can be used in combination with other technologies as infrared assisted heat pump drying, ultrasound assisted heat pump drying, and solar assisted heat pump drying. The processing and drying of food, the heating of crude oil in oil fields, the printing and dyeing industry, the distillation process, the pulp and paper industry, etc. are only a few additional uses for the heat pump. Improvement in efficiency of drying, ability to accurately control drying conditions, wide range of drying conditions, better product quality, increased throughput, and low operational cost are the key merits of the heat pump dryer.

Keywords: Agriculture, drying, heat pump, low temperature drying, shelf life

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1. Introduction

The oldest and largely used physical preservation method is drying, also known as dehydration or desiccation, which prevents the growth and activity of enzymes and microorganisms (Kovacı *et. al.*, 2020; Vardia *et. al.*, 2019). By reducing the moisture content in the product, drying helps to preserve the food material (Kohli *et. al.*, 2021). Drying has been used as a unit operation in a variety of sectors including food sector since ancient times (Moses *et. al.*, 2014; Shahi *et. al.*, 2022). The processes used and the dehydration conditions have a significant impact on the final product's quality attributes. Early harvesting, compact weight for transportation, management of the harvest season, and less room for long-term storage without deterioration are all made possible by the drying procedure (Kaveh *et. al.*, 2021). As a result, handling expenses are reduced, and ambient storage is made practical (Yarahmadi *et. al.*, 2020; Zheng *et al.*, 2021). Additionally, it prevents physical and chemical alterations while being stored. Drying methods include solar, convention, infrared, fluidized bed, vacuum, freeze, microwave oven, and heat pump system (Kohli *et. al.*, 2018). There are three techniques to remove moisture from the air: chilling it to condense water vapour, raising the total pressure to cause condensation, and exposing the air to a desiccant, which removes moisture by utilising variations in vapour pressures (Motevali *et. al.*, 2011). To transfer heat to the product that has to be dried, drying uses convection, conduction, or radiation alone or in combination (Kohli *et. al.*, 2017; Lee & Kim, 2008). The capacity to manage drying temperature and air humidity, as well as the possibility for energy savings, are the key benefits of heat pump technology (Chin *et. al.*, 2018; Jangam & Mujumdar, 2011; Minea, 2015; Patel & Kar, 2012). The speed and temperature of the drying air have a big impact on drying kinetics. (Venkatachalam *et. al.*, 2020). Numerous experts have already examined the drying kinetics of various fruits and vegetables such as cherry (Song *et. al.*, 2020), tomato (Hilphy *et al.*, 2021), sweet potato (Onwude *et. al.*, 2021), mint leaves (Kannan *et. al.*, 2021), lemon (Özcan *et al.*, 2021), mango

(Shende & Datta, 2020), green apple peel (Alibas *et. al.*, 2020), stevia (Bakhshipour *et. al.*, 2021), banana (Macedo *et. al.*, 2020), jujube (Wang *et al.*, 2021), etc.

Among the most significant issues facing modern society are energy and environmental damage (Sharayei *et. al.*, 2018). In this context, increasing the effectiveness of energy systems and reducing pollution are of the utmost importance. The need for creating and enhancing more effective systems is becoming more important due to the rising demand for energy. The primary energy users are process industries; nevertheless, a significant amount of heat produced in these businesses is wasted as heat. The drying is also quite energy-intensive, so novel drying techniques and energy-efficient dryers are required (Oladejo *et. al.*, 2021). Waste heat recovery heat pumps can be utilised in that situation to save energy and raise the temperature of the heat source. The processing and drying of food, the heating of crude oil in oil fields, the printing and dyeing industry, the distillation process, the pulp and paper industry, etc. are only a few additional uses for these heat pump (Farshi & Khalili, 2019).

2. Heat Pump

A heat pump is a device that uses refrigeration cycle to transfer thermal energy to the outside to heat or cool a system. The units that provide cooling are known as air conditioners. Therefore, heat pump is an efficient cooling or heating system. The main components of heat pump are compressor, condenser, expansion valve, evaporator and refrigerant (Fig 1) (Goh *et. al.*, 2011). The coefficient of performance (COP) identifies a heat pump's energy efficiency which can be calculated as (Chua *et. al.*, 2002):

$$\text{COP} = \frac{\text{useful heat output}}{\text{power input}} \quad \dots (1)$$

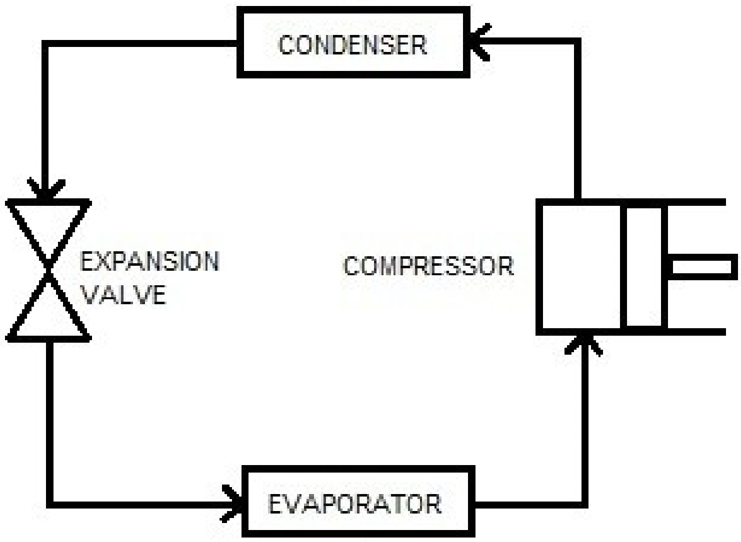

Fig 1. Heat pump cycle

3. Compressor: Main component

The major part of every heat pump system is the compressor, improving its performance may diminish the power input (Colak & Hepbasli, 2009). The one of the utmost efficient ways to advance the performance of compressor is cooling by using miniature heat pipes (Tunckal & Doymaz, 2020). Heat pipe transfers the heat from compressor cylinder head (the hottest region of compressor) to the oil reservoir. Additionally, the heat pipe transmits heat from oil to the outside. The performance of the entire heat pump system will be impacted by using a different refrigerant (Dong *et. al.*, 2022).

4. Types of Heat Pump

Among the most common heat pump cycles used in industry are vapour compression and absorption cycles (Farshi & Khalili, 2019). However, various limitations and challenges limit their applications. Compression heat pumps that rely on the compressor's mechanical labour have several drawbacks, particularly when the temperature differential between the source and sink fluids is substantial. These issues are high pressure ratio, a high compressor discharge temperature, and a decline in efficiency (Colak & Hepbasli, 2009). Additionally, thermally powered cycles for absorption systems have a restricted performance. In the typical compression and absorption cycles, the source of irreversibility is the transfer of heat at the constant temperature of the evaporator and condenser. Heat transfer does not take place at a constant temperature in the hybrid compression/absorption heat pump, which is a combination of two standard cycles (Farshi & Khalili, 2019).

5. Heat Pump Dryer

When utilised in conjunction with drying activities, heat pump dryers have a reputation for being energy efficient. The main benefits of heat pump dryers come from their ability to manage the temperature and humidity of the drying gas as well as their capacity to recover energy from exhaust gas. The most frequently reported dryers used in conjunction with heat pumps are batch shelf or tray dryers or kilns (for wood), but other types, such as fluid beds, rotary dryers, etc., may also be utilised. Heat pump dryers are distinctive heat recovery devices for drying applications because they can convert the latent heat of condensation into sensible heat at the hot condenser. The Specific Moisture Extraction Rate (SMER) is a performance metric frequently used to assess dryer performance (Chua *et al.*, 2002). It can be calculated as:

$$\text{SMER (kg/kWh)} = \frac{\text{amont of water evaporated}}{\text{energy input to the dryer}} \qquad \dots (2)$$

When compared to alternative drying systems, heat pump dryer has greater SMER values and drying efficiency, which are indicators of its energy efficiency. Higher SMER would then translate to lower operating costs, shortening the pay-back period for initial outlay. It offers closed control of the drying conditions in terms of air temperature, humidity, and flow rate in addition to being energy efficient. A growing trend is using HPD on several heat-sensitive plants. Heat pump-dried herbs had better colour and scent compared to various conventional dryers. When compared to commercially dried items, the sensory values for heat pump-dried herbs were almost two times higher (Chua *et. al.*, 2010; Goh et al., 2011).

5.1. Solar-assisted heat pump dryer

Solar technology when combined with the heat pump system for drying of the fruits and vegetables it improves the performance of the drying operation and quality of the final product. A solar heat pump drier with a 1.5 kW compressor can generate hot water and hot air for drying agricultural products. Solar collector and condenser dry the airflow. If a higher drying temperature is necessary, a backup heater is installed after the condenser. The heat pump's coefficient of performance can reach as high as 4-5, but under solar heat pump drying conditions, it can reach 6.45 (Hao *et. al.*, 2022).

5.2. Air source heat pump dryer

Evaporator serves as a dehumidifier and condenser serves as a heater in a typical heat pump system used by an air source heat pump dryer (Salehi, 2021).

5.3 Microwave assisted heat pump dryer

This system is one of the novel methods of drying which reduces the time requirement for the drying of product. Any material subjected to electromagnetic radiation will be heated up by the phenomena known as microwave heating. In order to heat food with a microwave, electromagnetic energy must be converted to thermal energy (Zhang *et. al.*, 2006). Food's ionic components and water molecules both translate as the microwave radiation is absorbed during heating. The heat is generated within the product. The use of microwave for drying of food shortens the drying time. The microwave assisted heat pump drying improves the drying characteristics, minimize the deterioration and also improves the quality of the final product. Additionally, in terms of energy use, heat pump-assisted microwave drying is comparable to traditional convective drying (Chua *et al.*, 2010).

5.4. Infrared assisted heat pump dryer

By supplying additional sensible heating to quicken the drying process, infrared (IR) drying aids to shorten the drying time. The advantages of infrared dying include: compact heaters are capable of producing high heat transfer rates, directing the heat source to the drying surface is simple, accelerated response times, enabling simple and quick process control (Kaveh *et al.*, 2021). The infrared assisted heat pump drying is simple and cost effective. It improves the quality of product, increases drying rate, minimizes color degradation, reduces drying time and helps to fast removal of surface moisture (Chua *et al.*, 2002).

5.5. Radio-frequency assisted heat pump dryer

Radio frequency accelerates the drying process by producing heat volumetrically within the wet material through the combined mechanisms of dipole rotation and conduction effects. A vapour compression heat pump system and a radio frequency producing system make up a radio frequency assisted heat pump dryer. The characteristics of this system include: it improves the color of products, evenly heats the product, reduces the drying time and cracking due to uneven shrinkage can be eliminated (Chua *et al.*, 2002).

6. Systems in heat pump dryer

6.1. Single-stage compressors

There are single-stage compressors used in the current refrigerant cycles or heat pump dryers. The temperature difference between the evaporator and condenser has a significant impact on the compressor's performance. One evaporator is employed in these systems to cool, dehumidify, and recover the latent heat of vaporisation. Additionally, the single-stage heat pump cycle cannot provide multiple streams of drying air with various drying conditions, including temperature and humidity (Colak & Hepbasli, 2009).

6.2. Multi-stage compression systems

Vapor-compression systems with multiple stages allows supplementary control mechanism to adjust air’s humidity. In two-stage, at the condenser exit the vapor of refrigerant splits into two streams to enter in two expansion valves, one to regulate low evaporator temperature and other to expand at higher temperature. In three stage system, the three evaporators are their one is at high and two is at low pressure side. This system is extremely beneficial to carry cold storage and drying process. Due to complexity, initial capital cost is high but for unit system capital cost is low as it carries numerous tasks simultaneously. Better heat recovery from the various drying and freezing chambers could lower the overall running expenses (Chua *et al.*, 2002).

7. Application in Food

The application of heat pump dryer in fruits and vegetables is shown in Table 1. The heat pump system has been studied and developed for a variety of uses, most notably for room heating, cooling, and dehumidification (drying). Heat pump dryer ensure the quality of final product (Goh *et al.*, 2011). Vapor compression heat pump dryers are widely used to reduce the energy consumption and cost for drying (Cheng *et. al.*, 2022). It has high coefficient of performance (COP), energy efficiency, and drying efficiency. It dries the product at low temperature in less time with less loss in quality. So can be used for heat sensitive products (Ren *et al.*, 2022). It can be used solely or in combination with other drying method such as solar, infrared, vacuum, and ultrasound assisted heat pump drying (Hao *et al.*, 2022). It has been used for drying of wide range of products such as mushroom, pineapple, kiwifruits, grapes, guava, etc (Salehi, 2021).

Table 1. Application of heat pump dryer in fruits and vegetables

S.No	Products	Methods	Results	References
1	Banana and potato chips	Batch-type heat pump dryer in Closed and open-cycle modes	1. Coefficient of performance (COP) and specific energy consumption is higher for open-cycle mode. 2. The specific moisture extraction rate (1.248 kg/kWh), drying efficiency, total exergy destruction, mass transfer coefficient and moisture diffusivity are higher for closed cycle drying.	Singh *et. al.* (2020)
2	Adzuki bean seeds	Ultrasound assisted heat pump intermittent drying	1. High germination percentage at low-temperature drying. 2. High power ultrasound causes structural damage and weaken the seed viability.	Yang *et. al.* (2020)
3	Antarctic krill	Heat pump drying and freeze-drying	1. Drying by combined dehydration had good color and microstructure. 2. It saves 62 and 50% of time and energy consumption, respectively.	Sun *et al.* (2017)
4	Apple	Heat pump, vacuum microwave, and combined drying	1. The convective vacuum microwave drying results in shortest drying time. 2. The effective diffusivity ranged from 3.522×10^{-8} to 1.431×10^{-6} m^2/min. 3. The combined heat pump vacuum microwave results in highest retention of antioxidant and total polyphenol content with the greatest appearance.	Chong *et. al.* (2014)
5	Apple	Heat pump and solar dryer	1. The effective moisture diffusivity was $1.03\times10^{-8} m^2/s$ for solar dryer and $2.36\times10^{-8} m^2/s$ for heat pump dryer. 2. Page model was found to be best to describe the drying characteristic	Aktaş *et. al.* (2009)

6	Guava	Modified atmosphere heat pump drying	1. Using carbon di-oxide, the effective diffusivity increases 44 % for guava and 16.34% for papaya during drying. 2. There was faster rehydration, less browning, and high vitamin C retentions in final produce.	Hawlader *et. al.* (2006)
7	Banana	Heat pump–assisted drying	1. With increase in drying temperature, drying time reduces while increase in slice thickness increases the drying time. 2. The effective moisture diffusivity varies from 1.05×10^{-10} to 1.56×10^{-10} m^2/s. 3. Activation energy found to be 42.58 kJ/mol.	Kushwah *et. al.* (2022)
8	Leaf	Heat pump drying	1. The coefficient of performance of a heat pump was 1.75. 2. The average specific moisture extraction rate is 0.038542 kg/kWh.	Babu *et. al.* (2022)
9	Mushroom	Heat Pump drying	1. Drying time at 55°C is the most important factor affecting the rehydration ratio 2. The drying time at 35 °C is the key factor affecting the coefficient of performance of the heat pump. 3. The optimal drying time at 35 °C, 45 °C, 55 °C, and 65 °C are 2.4 h, 3.3 h, 5.6 h, and 2.6 h, respectively.	Zhang *et al.* (2022)
10	Tomato	Heat pump dryer and microwave dryer	1. The microwave drying needs less time for drying 2. Heat pump drying is better choice from the sustainability point of view	Kumar *et. al.* (2022)

8. Factors to be consider for installation

Concerning elements while enhancing a heat pump drier are cost of installation, performance factors of drying such as relative humidity, temperature, velocity, and other assisted parameters for ultrasound, solar, and infrared (Chua *et al.*, 2010). The payback period and power requirement for system is also the important criteria. The considerations significantly improves product quality and reduce cost of operation (Goh *et al.*, 2011).

9. Merits and demerits of heat pump drying

9.1. Merits of Heat Pump Dryers

Table 2 describes the advantages of the heat pump drying system. Improvement in efficiency of drying, ability to accurately control drying conditions, wide range of drying conditions, better product quality, increased throughput, and low operational cost are the key merits of the heat pump dryer (Salehi, 2021).

Table 2. Advantaged of heat pump drying

S. No.	Advantages	Reason
1	Improves Efficiency	It recovers the latent energy and regenerated back to heat pump cycle results in energy conservation
2	Accurately control drying conditions	Independently controls air flow rate, temperature, and humidity which results good product quality
3	Wide operating range	Different temperature and humidity conditions
4	Good product quality	As it can dry the heat sensitive product at lower temperature
5	High throughput and low operation cost	Break-even period is low for lower operating cost and higher output volume

9.2. Limitations of Heat Pump Dryers

The use of CFCs as a refrigerant is an environmental concern but these refrigerants are now replaced with environment friendly refrigerants. The maintenance cost of heat pump dryer is high as it requires regular maintenance of the compressor, filter, and heat exchanger. In case of pressurized system, the refrigerant can be leaked due to cracking of pipes which will drop the pressure and effects the performance. The capital cost may be high compare to the other conventional dryers. Heat pump dryers' capacity to recover heat, however, results in cheaper running expenses, which balance the higher capital cost (Hao *et al.*, 2022).

10. Conclusion

Heat pump is used for heating and cooling of space. Drying is important unit operation for preservation. Heat pump drying is technique of drying with low energy consumption. By improving the coefficient of performance of heat pump system the drying performance can be changed. The heat pump drying method can be used for the heat sensitive products. Heat pump drying assisted with other techniques like solar, ultrasound, infrared etc might increase the performance of the system, and quality of the final product, but it will greatly increase the cost of operation. Improved efficiency of drying, ability to accurately control drying conditions, wide range of drying conditions, better product quality, increased throughput, and low operational cost are the key merits of the heat pump dryer.

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