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An Introduction of Biomimetic System and Heat Pump Technology in Food Drying Industry

Khurram Yousaf, Kunjie Chen and Muhammad Azam Khan

Abstract

Drying of food products is a relatively complex, nonlinear, and dynamic process due to simultaneous heat and mass transfer, rapid moisture evaporation, and biological and chemical reactions. Therefore, the monitoring of food quality during the drying process using bio-inspired technologies can play a vital role. The demand for high-quality dried food products and the rapid growth of energy in food processing are attracting new and renewable sources of energy. Energy efficiency, improved food product quality, and less environmental impact are always the main priorities of any drying system development. In-depth knowledge of biomimetic systems and drying kinetics would be helpful to design new dryers and technologies. Due to the excellent features (controllable drying temperature, drying time, drying air velocity, and relative humidity), heat pump drying systems have been used widely to ensure food and agricultural product quality. This chapter helps to understand the relationship between bio-inspired technologies and the role of heat pump technology in the food drying industry in terms of cost-effectiveness, energy saving, and better food product quality.

Keywords: heat pump, drying, biomimetic, food quality, energy efficiency

1. Introduction

Drying remains an essential part of food processing to enhance the shelf life of agricultural produce. To facilitate storage, preserve nutritional value, and add value in farm products, drying has been an essential solution [1]. Vegetables and fruits are one of the primary sources of vitamins and minerals. They have a high amount of nutritional components due to which they are considered a basic need for a balanced diet. Food products contained a high amount of moisture, such as vegetables and fruits, which have more than 80% and cereals more and less 30% [2]. Therefore, vast amounts of foodstuff deteriorate annually because of the inappropriate handling (pre- and postharvesting) and lack of processing facilities. Approximately 30–50% of losses occur in vegetables and fruits from field to consumer. The easy availability of fresh food to consumers for an extended period, process, and storage facilities are compulsory [3]. However, the increasing

infrastructure and processing cost of post-storage techniques are essential limitations. Due to increasing demand of high-quality food products, various conventional and mechanical food drying methods have been employed to process and protect from deterioration such as solar drying, oven drying, hot air drying, vacuum drying, freeze drying, microwave drying, infrared drying, and air source heat pump (ASHP) drying [4].

The ASHP drying system has two main components: an HP and a drying assembly—a functional HP system is composed of a compressor, condenser, evaporator, refrigerant, and throttle valve [5, 6]. Similarly, the drying system consists of the dryer and other necessary accessories. In the drying cycle, the materials to be dried are fed into the drying chamber and dehydrated until attained desired moisture content. In the HP cycle, the condenser provides the heat for the drying process by condensation of the refrigerant; similarly, the refrigerant absorbs heat and evaporates in the evaporator. The compressor of the HP compressed it again and delivered to the condenser to complete the cycle [7]. The hot heat generated by the condenser and cold heat by the evaporator can be used at the same time during the HP operation. The hot and cold heat from condenser and evaporator will be used to heat the product and dehumanization, respectively. Due to the excellent capability of the HP to convert the latent heat of vapor condensation into sensible heat of air makes it attractive in the drying industry. Many investigators recognized the utilization of HP in drying, which has attracted applied and theoretical research on drying using the HP [8–10].

The energy-saving capability and the ability to control air humidity and temperature are the main advantages of HP technology. These factors create options for variable drying conditions. Drying is one of the most energy-intensive practices, as it consumes up to 15% of industrial energy and 9–25% of national energy in developed countries [11]. About 40% of energy could be saved by using HP dryers as compared to electric resistance dryers. The drying process utilizes up to 70, 50, and 60% of total energy in the manufacturing of wood products, textile fabrics, and farm corn production, respectively [12]. Therefore, it is necessary to find out appropriate HP technology to reduce energy consumption. It has been reported that HP drying helps to improve product quality.

The performance of the HP system can be improved by the implementation of a sophisticated control strategy [13]. The three-layer ANN model has been used in the prediction of HP system performance. The study depicted that the application of ANN in the prediction of the HP system was consistent and robust [14]. Yang et al. [15] have used a simultaneous control strategy to improve the precision of drying temperature and superheat. A stable drying temperature was attained using two fuzzy controllers with different membership functions and control rules. The study revealed that the newly developed controller is reliable to reduce the nonlinearities of drying temperature and superheat. The yum slices of different thicknesses and longan were dried using the step-down and continues dehumidification strategies of controlling relative humidity [16]. It concluded that a step-down approach was found more energy efficient for 12 or 18 mm thickness, whereas a continuous decrease of relative humidity strategy was found energy efficient for longan, respectively.

Besides these drying systems, smart drying mechanisms (biomimetic systems) can be cost-effective in controlling various foodstuffs quality parameters with variable drying process time. The quality of food products can be assessed through many senses such as appearance, smell, and taste. The human sense inspired systems including electronic noses (odor sensing technology) and electronic tongues (taste sensing technology) are extensively under considerations

by researchers and scientists for different food processing steps, e.g., drying, packaging, and storage. These biomimetic systems provide reasonable information on odor and taste to analyze the quality of food products. The combination of these biomimetic systems, computer software, and data analysis methods exhibits environment-friendly, cost-effective, and multifunctional results for food quality control. Many studies highlighted the significance of HP technology in terms of energy efficiency, cost-effectiveness, and product quality. However, there is a need to summarize the technological advancement of the HP drying system in the food industry. The HP drying system can be more sophisticated and attractive if coupled with biomimetic odor and taste sensing systems for food safety and quality. This chapter presents the recent developments in HP drying technologies of food products, studies these advancements to maintain the food quality, and further discusses the research potential in this field.

2. HP drying and its application in the food industry

2.1 HP drying

Heat pumps raise the energy gained from the low-temperature level to high-temperature level and transfer it to the energy carrier medium. In an HP, both the heating and cooling processes of the refrigerator are utilized. Nowadays, HP technology is used in the domestic and commercial sectors for space heating and cooling such as in offices, water heating, swimming pools, commercial drying in agriculture, and the wood industry as well as the cotton industry. The main objective of the utilization of HP technology in the food drying sector is to dehydrate the food products for quality enhancement at minimum cost. HP drying technology is one of the most efficient and controllable methods of water extraction from the material. The research and development in HP technology have improved its performance. HP drying technology has been modified to air source HP drying, ground source heat pump drying (GSHPD), chemical source heat pump drying (CSHPD), and hybrid heat pump drying (HHPD), as shown in **Figure 1**. The following chapter reflects the contribution of significant HP technologies in the food drying sector.
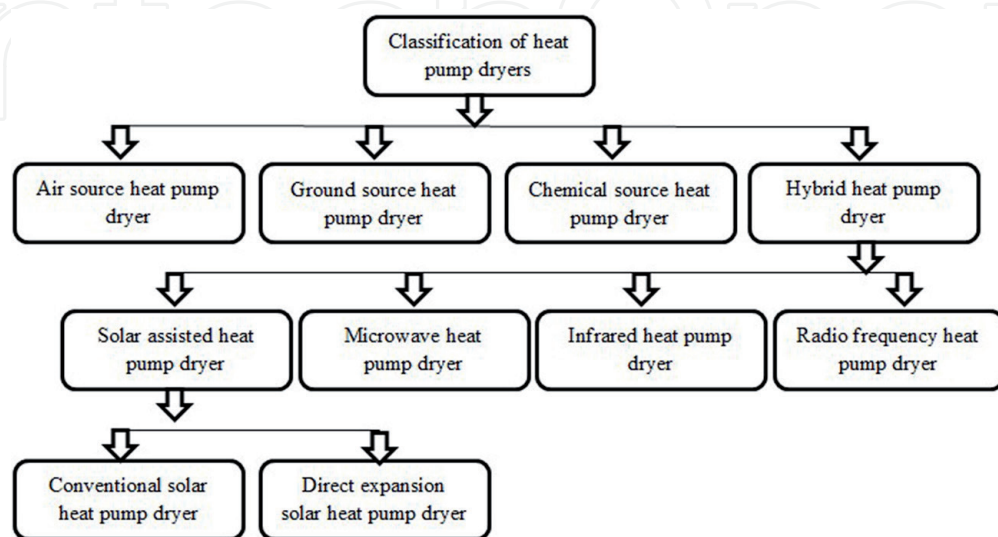

Figure 1.
The primary classification of heat pump dryers [17].

2.2 Performance indicators of HP drying system

2.2.1 The coefficient of performance

The coefficient of performance (COP) of the HP system refers to estimate the performance during heating conditions. In an ideal model, the heating of hot air in the drying chamber is a hot air adiabatic cooling process as follows:

$$c_p \left(T_{dr,a,in} - T_{dr,a,out} \right) = \left(d_{dr,a,out} - d_{dr,a,in} \right) r_s \tag{1}$$

In actual condition, enthalpy change occurs during hot air passed through the drying chamber as follows:

$$\Delta h_{dr,\,a} = c_p \left(T_{dr,\,a,\,in} - T_{dr,a,\,out} \right) - r_s \left(d_{dr,\,a,\,out} - d_{dr,a,\,in} \right) \tag{2}$$

For materials,

$$DR = \frac{M_t - M_{t-\Delta t}}{\Delta t} \tag{3}$$

During the hot air cycle, two heat exchange processes occur in the HP drying system, as follows:

$$Q_{evap} = m_{evap,a} C_{p,a} \left(T_{evap,a,in} - T_{evap,a,out} \right) \tag{4}$$

$$Q_{cond} = m_{cond,a} C_{p,a} \left(T_{cond,a,out} - T_{cond,a,in} \right) \tag{5}$$

where

$$C_{p,a} = 1.01 + 1.84d \tag{6}$$

$$W_h = m_a \left(h_{dr,a,in} - h_{HP,a,in} \right) \tag{7}$$

$$W_{comp} + W_h = m_a \Delta h_{dr,a} + \Delta Q_{HP} \tag{8}$$

$$W_{comp} + W_h = m_a \left(\Delta h_{dr,\,a} + h_{HP,a,out} - h_{HP,a,in} \right) \tag{9}$$

The compressor power and speed can be controlled by motor frequency. The COP of the HP and the whole system can be measured using the following relationships:

$$COP_{hp} = \frac{Q_{cond}}{W_{copm}} \tag{10}$$

$$COP_S = \frac{Q_{cond}}{\sum W} \qquad (11)$$

2.2.2 Specific moisture evaporation rate

The ratio of water removed from material to total energy consumption is termed a specific moisture evaporation rate (SMER). The HP drying system must apply energy and dehumidified material. It must be measured to evaluate the performance of the heat pump drying system. The SMER (kg/kWh) is given as follows:

$$SMER = \frac{M_{evp}}{W_h + W_f + W_{comp}} \qquad (12)$$

2.2.3 Moisture extraction rate

It is defined as water extracted from material to the total time of material drying in the chamber and expressed in kg/h. Moisture extraction rate (MER) is one of the important factors to evaluate the HP drying system performance. MER can be calculated as follows:

$$MER = \frac{M_{evp}}{t_{dr}} \qquad (13)$$

2.3 Air source heat pump drying of food

An air source HP dryer works on a simple principle of HP technology with the condenser as a heat source and evaporator as a dehumidifier. Liu et al. [6] designed a multifunctional air source HP dryer and investigated the drying performance of 3-mm thickness garlic slices in three different ambient temperature and humidity conditions. The drying rate and energy consumption of the HP drying system were investigated by utilizing different hot air circulation modes using an enthalpy-humidity diagram.

An air source HP drying system not just depends on the HP but also the circulation style of the drying medium. According to the circulation style and degree of ventilation, ASHP dryer can be divided into open, semi-open, and closed types. The exhaust gas flowing out of the drying chamber contains a high amount of heat; the temperature of exiting gas is usually higher as compared to the ambient temperature. As a result, it is essential to pass the exiting gas through the evaporator of the HP to increase the thermal efficiency of the HP drying system. Sometimes, it restricts the heat exchange due to dust particles adhered to the surface of the evaporator. BAR can be adjusted by changing the degree of opening and closing of duct valves. The BAR can be expressed as follows:

$$BAR = \frac{a_{bypass}}{a_{through\ evaporator}} \qquad (14)$$
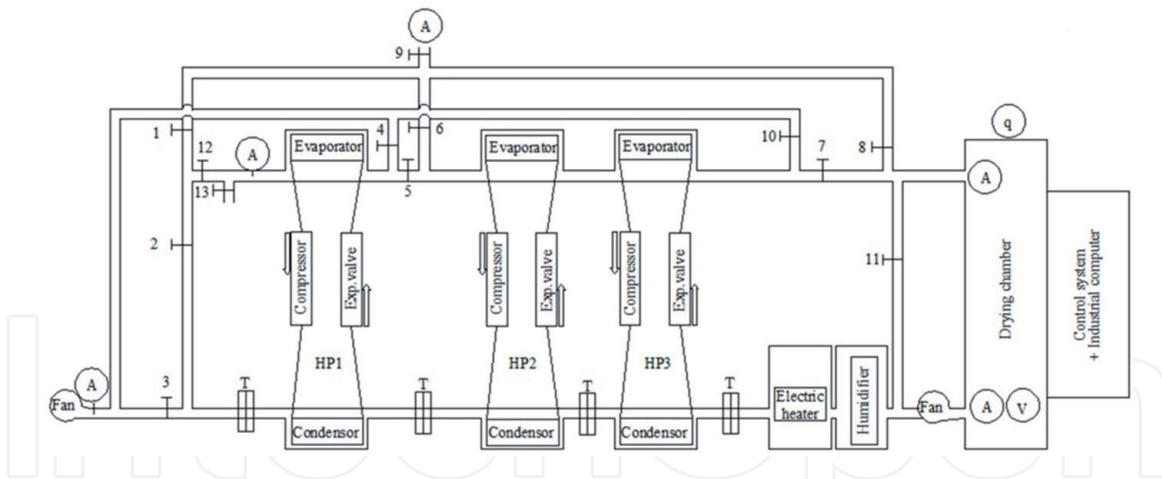
Figure 2.
Air source heat pump dryer test bench with a series of heat pump units [5]. (A = temperature and humidity sensors, q = quality sensor, V = air flow sensor, HP1, 2, 3 = heat pump units, T = temperature sensors, and 1–13 = air duct valves).

Yousaf et al. [5] used the HP dryer test bench with a series of heat pumps for parboiled rice drying of different varieties and sample loads, as shown in **Figure 2**. SMER, MER, and COP of HP dryer were calculated and analyzed in open and closed cycles. The COP of the closed-loop cycle (2.211) drying was higher than open-loop cycle (1.409) because fresh air entered into the system during the open-loop cycle. Saensabai and Prasertsan [18] conducted a simulation study of five different configurations of the air source HP. Soponronnarit et al. [19] reported that COP_{hp} and SMER enhanced with 0% BAR and reduced with increasing of BAR during paddy seed drying. Chapchaimoh et al. [20] utilized the closed system HP dryer for ginger drying, where air and nitrogen were used as a drying medium. The study concluded that SMER in air and nitrogen was 0.06 and 0.07 kg H_2O/MJ, respectively. Similarly, energy consumption for air and nitrogen drying was 16.67 and 14.29 MJ/kg, respectively. Many studies have been done on drying of food products using different HP technology systems, as shown in **Table 1**.

2.4 Ground source or geothermal heat pump drying of food

Recent developments in HP technology made it attractive for researchers to conserve energy and processing time. The geothermal HP system can save 44 and 70% energy as compared to air source heat pumps and air conditioning and conventional electrical heating [54]. The ground source heat pump (GSHP) drying system is relatively similar to the ASHP drying system with the addition of a ground source heat exchanger, as shown in **Figure 3**. The following system extracts heat from the ground by a ground source heat exchanger with the help of a circulated antifreeze water solution. The extracted heat is transferred to refrigerant in the evaporator and delivered to the food drying chamber. However, few studies on GSHP drying of food have been reported.

Colak et al. [29] designed a GSHP dryer unit for a single layer of mint leaves drying. The drying system was designed and developed in Solar Energy Institute, Ege University, Izmir, Turkey. The mint leaves were dried at three different drying temperatures 40, 45, and 50°C, constant relative humidity of 16%, and mass flow rate range of 0.01–0.05 kg/s. It revealed that the highest exergy efficiency (97.24%) was achieved at maximum temperature (50°C) and a mass flow rate of 0.05 kg/s. Another researcher studied the energy and exergy analysis of the GSHP drying

Sr. no.	Researcher	Food product	Heat pump dryer type	Reference
1	Achariyaviriya et al.	Papaya glace	Air source heat pump	[21]
2	Aktas et al.	Apple	Vapor compression cycle	[22]
3	Artnaseaw et al.	Chili	Vacuum heat pump	[23]
4	Artnaseaw et al.	Shiitake mushroom	Vacuum heat pump	[24]
5	Best et al.	Rice	Solar-assisted vapor compression cycle	[25]
6	Chen et al.	Lemon	Vapor compression cycle	[26]
7	Chua et al.	Guava and banana	Two-stage heat pump	[27]
8	Colak and Hepbasli	Apple	Ground source heat pump	[28]
9	Colak et al.	Mint leaves	Ground source heat pump	[29]
10	Cunney and Williams	Grain	Air source heat pump	[30]
11	Fatouh et al.	Jew's mallow, spearmint, and parsley	Air source heat pump	[31]
12	Hancioglu and Hepbasli	Laurel leaves	Ground source heat pump	[32]
13	Hawlader et al.	Yam	Air source heat pump	[33]
14	Hawlader et al.	Food grains	Air source heat pump	[34]
15	Hawlader and Jahangeer	Green beans	Air source heat pump	[35]
16	Hawlader et al.	Apple and guava	Dual condenser vapor compression cycle	[36]
17	Ho et al.	Potatoes	Air source heat pump	[37]
18	Icier et al.	Agriculture broccoli floret	Dual condenser vapor compression cycle	[38]
19	Icier and Erbay	Olive leaf	Dual condenser vapor compression cycle	[39]
20	Jia et al.	Foam rubber, sliced carrots, and root	Air source heat pump	[40]
21	Pal et al.	Green sweet pepper	Dual condenser vapor cycle	[41]
22	Prasertsan and Saen-saby	Red pepper	Atmospheric freezer heat pump	[42]
23	Queiroz et al.	Tomatoes	Air source heat pump	[43]
24	Rahman et al.	Peas	Dual condenser vapor compression cycle	[44]
25	Rossi et al.	Vegetables	Air source heat pump	[45]
26	Shi et al.	Horse mackerel	Air source heat pump	[46]
27	Soponronnarit et al.	Papaya glace	Air source heat pump	[47]
28	Teeboonma et al.	Papaya and mango	Dual condenser vapor compression cycle	[48]
29	Vazquez et al.	Grapes	Vapor compression cycle	[49]
30	Zhang et al.	Carrot cubes	Air source heat pump	[50]

Sr. no.	Researcher	Food product	Heat pump dryer type	Reference
31	Aktas et al.	Mint leaves	Air source heat pump	[51]
32	Erbay and Hepbasli	Fresh laurel leaves	Ground source heat pump	[52]
33	Taşeri et al.	Grapes	Air source heat pump	[53]
34	Yousaf et al.	Paddy	Air source heat pump	[5]
35	Liu et al.	Garlic slices	Air source heat pump	[6]

Table 1.
Heat pump drying application in different food product drying.
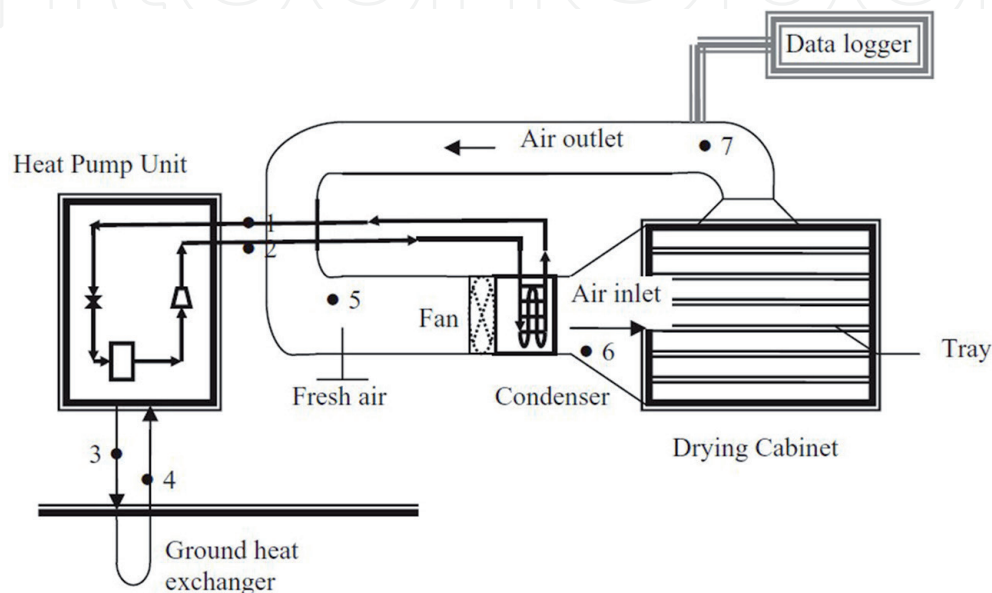
Figure 3.
Schematic diagram of ground source heat pump food drying system [29]. (1) Evaporator temperature and pressure; (2) condenser temperature and pressure; (3) fluid temperature at the ground heat exchanger inlet; (4) fluid temperature at the ground heat exchanger outlet; (5) fresh air temperature and humidity; (6) air inlet temperature and humidity; and (7) air outlet temperature and humidity.

system during laurel leaves drying. The COP of the GSHP and the whole system is in the range of 1.63–2.88 and 1.45–2.65, and SMER and SMExR of the system are in the range of 0.122 and 5: 11 kg/kWh respectively [55].

2.5 Hybrid solar-assisted heat pump drying of food

Sun drying has been used for food drying purposes for decades in tropical and subtropical countries, where solar energy is used as a primary source of energy to preserve fruits, vegetables, and other agricultural products. The traditional drying of food products by direct exposure has limitations, such as spoilage due to inappropriate climate conditions, waste of food due to the animal, birds, insects, and, most importantly, uncontrollable temperature and humidity conditions. The advancement of research and development in science and technology has changed the world; researchers and scientists are trying to find out the ways to reduce energy consumption in food processing and conservation. These globally renowned challenges in the food industry help researchers to design a hybrid drying system. Solar-assisted heat pump (SAHP) dryers are the best alternative to overcome energy crises challenges in the food industry [56]. According to literature, many studies have been done on the hybrid solar-assisted drying system, such as forced convection [57–61], solar-assisted auxiliary air heater dryer [62–64], and chemical heat pumps (CHP).

A SAHP dryer consists of a vapor compression cycle unit combined with a solar collector and drying chamber having a high coefficient of performance, as shown in **Figure 4** [65–67]. There are different kinds of SAHP dryers, depending on design, use, and material to be dried. The combination of the HP dryer and solar collector with the availability of solar energy can increase the energy efficiency and temperature of the drying system. Troger and Butler [68] studied the solar collector cum rock bed storage system for peanut drying. Gan et al. [69] studied the drying kinetics and quality of Misai Kucing leaves, stem, flowers, and mix components and compared the SAHP drying with conventional solar drying. The results were evidence of the change in color and loss of two bioactive components by solar drying. However, these changes were not seen in SAHP drying. The reason could be the higher drying temperature, long processing time, and degradation of chlorophyll.

Best et al. [70] developed a modified 7-kW air conditioning unit combined with a solar collector for rice drying. Another study of mushroom drying using a SAHP system with a flat plate solar collector and a GSHP system has been reported in the literature. Heat pump system, solar system, and SAHP system were employed for mushroom drying at 250–220, 270–165, and at 230–190 min, respectively. A computer program and PLC were used to control and monitor the relative humidity, drying air temperature, and weight of material to be dried. The mushrooms were dried from initial moisture 13.24 to 0.07 g (dry basis) using two different drying air temperatures of 45 and 55°C and 310 kg/h mass flow rate. SMER, energy utilization ratio, and COP were found to be in the range of 0.26–0.92 kg/kW h, 0.42–0.66, and 2.1–3.1, respectively [71]. Saffron drying has been studied in Iran using a solar-assisted hybrid photovoltaic thermal HP dryer. The system performance was investigated using variable drying air temperature (40, 50, and 60°C), mass flow rate (0.008, 0.012, and 0.016 kg/s), and drying modes with or without an HP. The study reported that using an HP, maximum dryer efficiency (72%) and SMER (1.16) were observed at drying air temperature of 60% and mass flow rate of 0.016 kg/s. Moreover, with the increase of drying air temperature and mass flow rate, energy consumption and drying time reduced. It also revealed, when dryer equipped with an HP, the average energy consumption decreased by up to 33% [72].
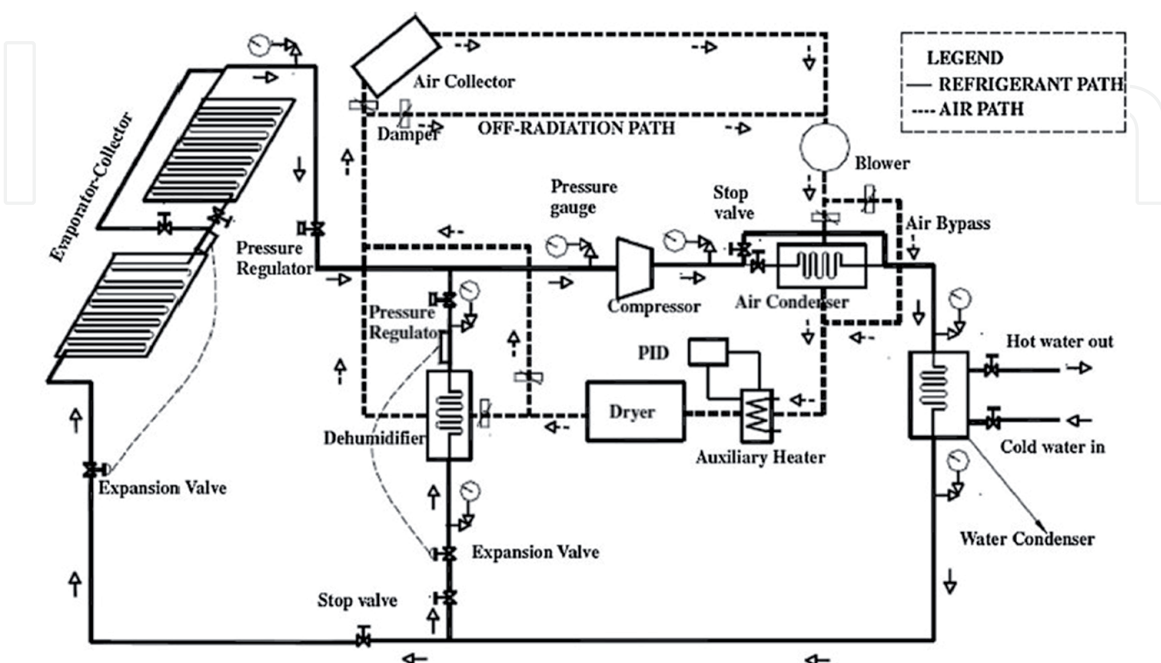

Figure 4.
Solar-assisted heat pump drying system [35].

3. Conclusion

Considering the drying kinetics of food products, HP technology is the best option for new demands of energy efficiency, product quality at a lower cost, and lower environmental impact. Many studies have discussed the HP system for food drying and concluded that HP drying systems are suitable for heat-sensitive products. The biomimetic systems are contributing as a key element in smart drying processes and becoming a very useful factor in the food drying industry. However, it has some limitations in its widespread applications in food drying industry. In the case of a bio-inspired electric nose, its sensing ability is greatly affected by humidity, background noise, temperature, sensor poisoning, and sensor variations. This chapter reported the contribution of HP technology in food drying. The demands of high-quality food products and energy-efficient technologies for food processing are increasing day by day. The future work on biomimetic systems and HP technology would allow researchers to produce more automated food drying plants involving innovative intelligent approaches. It can be seen in this book chapter, research and development in HP drying have improved to hybrid type HP dryers. No doubt, the performance of these hybrid systems has increased but would increase installation and processing costs.

Acknowledgements

Conflict of interest

The authors declare no conflict of interest.

Nomenclature

HP	heat pump
ASHP	air source heat pump
GSHP	ground source heat pump
SAHP	solar-assisted heat pump
CSHP	chemical source heat pump
BAR	bypass air ratio
SMER	specific moisture evaporation rate
MER	moisture extraction rate
ANN	artificial neural network
COP	coefficient of performance
Q	heating capacity (kW)
d	absolute humidity (kg water vapor/kg dry air)
rs	evaporative latent heat of water (kJ/kg)
m	mass flow rate (kg/s)
C_p	specific heat (kJ/kg K)
W	power (kW)
T	temperature (°C)
h	enthalpy (kJ/kg)
t, Δt	time (h)

Subscripts

a	air
evap	evaporator
f	fan
comp	compressor
s	whole system
dr	dryer, drying
cond	condenser
out	outside
in	inside

Author details

Khurram Yousaf[1,2]*, Kunjie Chen[1]* and Muhammad Azam Khan[3]

1 College of Engineering, Nanjing Agricultural University, Jiangsu, China

2 Atta-ur-Rahman School of Applied Biosciences, National University of Sciences and Technology (NUST), Islamabad, Pakistan

3 Department of Farm Machinery and Power, Faculty of Agricultural Engineering and Technology, University of Agriculture Faisalabad, Faisalabad, Pakistan

*Address all correspondence to: khurramyousaf@njau.edu.cn
and kunjiechen@njau.edu.cn

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