Review Article

Evaluation Beyond a Review: Developments in Heat Pump Dryers from the Recent Past to the Present

ABSTRACT

Countries that enter the technology race for a sustainable economic development are facing a serious crisis in the supply of energy sources and food products caused by the global covid-19 epidemic and drought in the last few years. This situation threatens global energy and food supply security. However, every crisis encountered can also create new opportunities for some sectors. The bottleneck in the food supply can be overcome by the widespread consumption of dried food products. In the drying sector, which is an energy-intensive process, the use of more efficient, more economical, and more environmentally friendly heat pumps provides excellent advantages. Studies on heat pump dryers for many years still maintain their popularity today. Heat pump dryers, the usage amount of which increases every year, are further developed with research studies. At this point, the studies that have been bought to the literature on heat pump dryers in recent years have been examined in a broad perspective. Thus, an important guide study has been put forward for researchers working on this subject and the sector leaders.

Keywords: Heat pump, dryer, energy, exergy, performance, review

1. INTRODUCTION

The drought in recent years and the loss of workforce caused by the threat of the global pandemic have caused a decrease in the amount of agricultural production on a global scale. This negative situation we are facing is a serious threat to global food supply security. In addition, currently, 25-30% of food products become waste after harvest in agricultural production without being consumed [1]. One of the most important reasons for this is that fresh vegetables and fruits should be consumed in a short time after they are harvested.

At this point, drying, which has been used in the process from ancient times to the present, is one of the most effective food preservation methods. The drying of fruits and vegetables is primarily converted into a commercial product that provides economic input by preventing the products from being wasted. In addition, the shelf life of the products increases, the storage, and transportation costs decrease with the decrease in the volume occupied by the products, and the taste and nutritional values of food products, which are as important as these, are preserved. In developing countries, the share of drying in the total amount of energy consumed in the food production and processing sector varies between 12-40% [2-4]. As can be understood from here, the food drying method is an energy-intensive process. In industrial food drying applications, fossil-based energy sources are generally preferred. However, disadvantages such as high cost, fluctuating prices due to current political developments, limited reserves and environmental damage are the most significant challenges encountered in the use of these energy resources. Using and disseminating more effective and innovative drying technologies has a key role in this context.

Solar energy is mostly preferred after fossil-based energy sources in drying. However, the inability of solar dryers to perform drying during the night and cloudy days is a problem that must be overcome. At this point, heat pump dryers are an ideal solution for continuous drying. Although the discovery of the heat pump is based on many years, its use has been limited. However, it has been a widely used method in the fight against the energy crises and global warming threat in recent years. Heat pumps are used in space heating and cooling applications, greenhouse heating applications, and drying of a wide range of products.

In this review study, recent developments and studies contributing to the literature about heat pump dryers are discussed. Namely, although there were a few review studies on this drying method before 2010 [5] and in the early 2010s [6-9], these studies were limited, and almost ten years have passed since this period. So much so that a great deal of work has been done on heat pump dryers only in this decade. These studies in the literature discussed in this review study were examined in terms of design, optimization, comparative performance evaluation, thermodynamic, economic, and environmental aspects. The performance of the heat pump dryers in these evaluated studies was examined in terms of moisture extraction rate (MER), specific moisture extraction rate (SMER), coefficient of performance (COP), specific energy consumption (SEC), total energy consumption (TEC), exergy destruction and efficiency, pick-up efficiency, etc. (Figure 1).

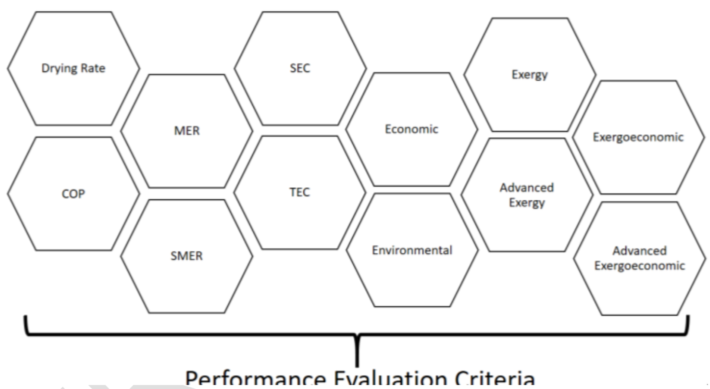

Fig. 1. Performance evaluation criteria of heat pump dryers examined in this study

2. HEAT PUMP DRYER SYSTEMS

The most crucial goal in the drying process is to consume the least amount of energy and to dry the maximum amount of product in the shortest time. In other words, it is to keep energy costs as low as possible. In this case, solar energy comes to mind first. However, although the energy input cost is very low, the inability to perform uninterrupted drying with this drying method prolongs the drying time. Also, more workers and more drying areas are needed. Products dried in the open sun are exposed to the harmful effects of dust, garbage, insects, flies, pests, and predators such as birds. On the other hand, the heat pump drying method is an efficient system that reduces the drying time when the processing cost is sustainable. With heat pump dryers, drying air temperature, humidity and speed can be kept under control. Since it is not a form of drying open to the atmosphere, it is not affected by adverse meteorological conditions. Heat pump dryers both dehumidify and raise the drying air temperature. In addition, the product quality can be maintained by drying at low temperatures.

2.1. Working Principle of Heat Pump Dryers

Heat pump drying systems can generally be expressed as the integration of the drying chamber and the heat pump system. Compressor, evaporator, expansion valve, condenser, and drying chamber are typically the main elements in heat pump dryers. Heat pump dryers are designed in open, closed, and semi-open loop arrangements. As shown in Figure 2a, an open loop heat pump drying system has a drying air circuit and a heat pump circuit. While the air taken from the atmosphere passes through the evaporator, it transfers its heat to the working fluid in the heat pump circuit and then proceeds to the drying chamber through a separate channel. At the same time, the working fluid is compressed in the compressor up to condenser pressure, and its temperature is increased, then sent to the condenser. The working fluid transfers its heat to the drying air passing through the condenser and raises the temperature of the drying air. Afterward, the drying air enters the drying chamber, comes into contact with the products, and is evacuated to the atmosphere by removing the moisture of the products. In closed-loop heat pump dryers (Figure 2b), the humid drying air coming out of the drying chamber is not vented to the atmosphere and is passed through the evaporator in the heat pump circuit through a channel. Here, the drying air's moisture is condensed, and its latent and sensible heat is utilized. Afterward, the drying air passes over the condenser before entering the drying chamber, where it gains heat and increases its temperature. Finally, the dying air comes into contact with the products to be dried and absorbs moisture, and the cycle is completed.

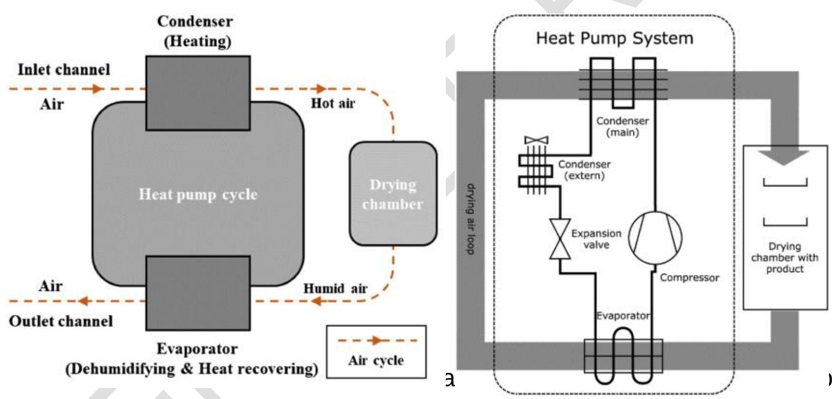

Fig. 2. (a) Open-loop heat pump dryer [10], (b) closed-loop heat pump dryer [11] schematic representation

2.2. Classification of heat pump dryers

Air, ground, lakes and streams, and waste heat can be counted as heat sources for heat pumps. A diagram classifying heat pump dryers are given in Figure 3 [6]. Accordingly, we can divide the heat pump dryers into four main headings: air, ground, hybrid source, and chemical heat pump.

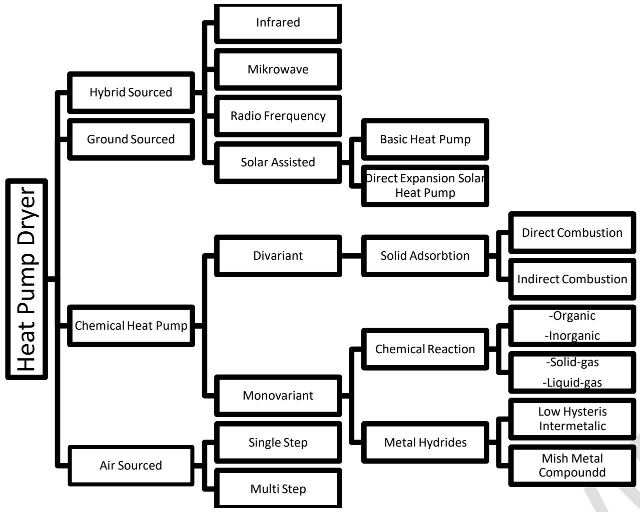

Fig. 3. Classification of heat pump dryers [6]

3. ASSESSMENT OF THE PERFORMANCE OF HEAT PUMP DRYERS

3.1. General Studies on Evaluation of the Performance of Heat Pump Dryers

There are many studies on the performance evaluation of heat pump dryers. In some of these studies, banana [12,13], tomatoes [14], carrot [15], paddy [16], sweet pepper [17], hawthorn [18], moringa leaves [19], fish [20], orbeez [21,22], clothes [23-26] and many crops were successfully dried. Detailed information about these studies is summarized in Table 1. When the literature on heat pump dryers is examined, ambient air is generally used as a heat source. Heat sources such as ground and water remained limited. For this reason, the compiled studies are not divided into sections such as air, ground, water, etc., according to the heat source. Important information about the studies investigated the performance of heat pump dryers selected from the literature are presented below in mini-summaries.

Wongwises et al. designed, manufactured, and measured a heat pump dryer's performance [32]. R22 is used as the working fluid in the heat pump circuit. In the experiments, shiitake mushrooms were dried. They determined the COP and SMER of the heat pump. Optimum working conditions were determined by using the air recirculation percentage. Finally, the key parameters affecting the performance and drying speed of the system were determined. Fatouh et al. designed and manufactured a heat pump dryer to experimentally analyze the drying characteristics of jew's mallow, parsley, and spearmint [33]. The working fluid is R134a. The effect of herbs height, surface load, stem presence, drying air velocity, and temperature on the samples drying properties and dryer efficiency were investigated. Maximum dryer productivity of approximately 5.4 kg/m^2h was achieved at 55℃, 2.7 m/s drying air condition, and 28 kg/m^2 dryer surface load. Phoungchandang ve Saentaweesuk measured desorption isotherms for sliced ginger [34]. The authors used a nonlinear regression program to fit the four moisture sorption isotherm models to the experimental data. Modified Oswin and Modified Halsey models showed the best fit. They performed tray and heat pump moisture-free drying in one- and two-stage trials. Dehumidified heat pump drying combined with two-stage drying reduced drying time by 59.32% at 40°C.

Table 1. Some studies in the literature on heat pump dryers

Product	İnit. Moist.	Final Moist.	Drying Conditions	Drying Time	Highlight Outputs	Ref.
Banana	75.5%	18%**	30-50℃/1.5-3 m/s	450 min+	COP:4.7	[12]
Carrot			30,35,40℃/1 m/s /15% rh	315/294/281 min		[15]
Tomatoes	15.667	0.865*	35,40,45℃/1 m/s	12/10/7 h	COP:2.71 SMER:0.324 kg/kWh,	[14]
Paddy	30%	14%**	42,46℃/1800m^3/h	15 h	SPC:1663kJ/kg	[16]
Hawthorn	0,99	0,3*	60-65℃/ 1.5-3 m/s	120-130 min	COP:3.45.SMER:0.93 kg_w/kWh	[18]
Sweet Pepper			30-41℃/27-40% rh	16-36 h	SMER:0.55-1.1 kg_w/kWh, EC:4.48-4.05 kWh,	[17]
Moringa leaves	81%		1.1-1.4 m/s/0.8-0.9 bar	-	26.04% increase in evaporation rate relative to drying air speed	[19]
Orbeez	98-99%	94-97%**	48-58℃/ 3-8 kg sample	8 h	COP:5.2-5.8 HTR:0.56-0.64 kW MER:0.66-0.75 kg/h	[21]
Tomatoes	23**	0.1	40,45,50℃/10-15%	100 min	COP: 2.56-2.68	[27]
Paddy	30-35%	13%**	26,42℃/26,14% rh	15-16 h	MER:8-15.9 kg_w/h, SMER:2 kg_w/kWh	[28]
Garlic	1.63-1.88	0.06*	37-40℃/ 1 m/s/ 3-5% rh	10-13 h	-	[29]
Saffron	80%	10%**	40-60℃/	30 min	SMER:0.5-1.1 kg_w/kWh	[30]
Apple		10%	50℃/ 2 m/s	95 min	SMER:2.26 kg_w/kWh MER:0.54 kg_w/h SEC:1.6 MJ/kg_w	[31]

**Moisture content on dry basis, **Moisture content on wet basis, SPC: Specific Power Consumption, rh: Relative Humidity*

Doungporn et al. developed a drying equation to predict the thin layer drying kinetics of Thai Hom Mali paddy dried in CO_2 and N_2 gases [35]. The Thai Hom Mali paddy and Khao Dok Mali 105 with an initial moisture content of 32% (d.b.) were dried in a heat pump dryer under drying air at 40, 50, 60, and 70℃, at a surface velocity of 0,4 m/s, at constant 60% by-pass air. While the drying rate is not effected by the drying gases, it increases with temperature change. Moisture rates compared between Modified Page I, Page, Newton, Henderson and Pabis, diffusion approximation, two-term, and Midilli models at any time during the drying operation. The one-step regression method determined the impact of drying air temperatures on the coefficients of the best humidity model. The most compatible model illustrating the drying behavior was Midilli.

Hii et al. investigated the drying kinetics of cocoa beans called testa and cotyledons in a heat pump dryer [36]. They dried the samples as a thin layer in dehumidified air at 28.2, 40.4, and 56℃. In the product quality analysis, the percentage retention of cocoa polyphenols compared to the freeze-dried sample ranged between 44-73%. It was noted that the core hardness was understandably comparable to the commercial sample an increased with decreasing moisture content. Shi et al. investigated the drying quality and kinetics properties of yacon in a heat pump dryer at different dying air temperatures (5, 15, 25, 35, and 45℃) and velocities (0.5, 1, 1.5, and 2 m/s) [37]. The drying time reduced with increasing air velocity and temperature. Eight different mathematical models were used to define and compare the yacon's drying kinetics. The most compatible model was Midilli. They described the transferred moisture of yacon slices by implementing Fick's diffusion model.

Sheng et al. built and tested the desiccant wheel system, high-temperature heat pump, and associated air conditioning unit to solve the trouble of high energy consumption in the regeneration of the dryer wheel in the rotary dryer system, schematically drawn in Figure 4b [38]. The authors stated that the outdoor temperature, humidity, and regeneration airflow rate have a great influence on the heat pump's performance based on COP. The maximum COP value for the heat pump was found to be 2.26, and for the whole system, this value was found to be 2.08. Juan et al. designed, manufactured, and researched a heat pump dryer's performance for drying mushrooms [39]. It has been determined that the air distribution in the lower part of the drying chamber is more uniform. 75.2 kg of water was evaporated from 90 kg of fresh mushrooms in the experiment. While this process took 670 min., 33.2 kWh of electricity was consumed. For the whole drying system, SMER was calculated as 2.3 kg/kWh, and when only the compressor's electricity consumption was taken into account, this value was calculated as 3.5 kg/kWh.

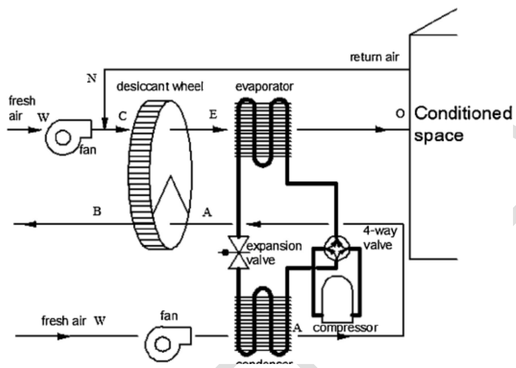

Fig. 4. High-temperature heat pump dryer and desiccant wheel [38]

Yamankaradeniz et al. designed, built, and tested a circulating heat pump dryer system at steady-state and transient conditions [40]. R134a was used as the working fluid. The authors investigated the effect of by-pass air ratio (BAR) on system performance and system parameters such as the steady-state SMER value. The impacts of drying air temperature and relative humidity changes on time-dependent system parameters were investigated. The parameters of the system did not change up to 40% of BAR. Depending on the BAR, the SMER, and COPsyst. varied between 1.2-1.4 and 2.8-3.3, respectively. During the drying process, COP and SMER values decreased depending on time. Chapchaimoh et al. discussed the performance and energy consumption of a closed system heat pump dryer for drying ginger at 50℃ for 200 min in air and N_2 drying ambient [41]. For N_2 and air cycles, the heat gained in the internal condenser is 20.5 and 15.4 MJ, and the heat exhaust in the evaporator is 22.9 and 18.6 MJ, respectively. For N_2 and air medium, the heater provides 65.6% and 62.93% of the total energy input of the working fluid cycle, respectively, while the heat recovered in the external condenser is 28.79% and 37.92%, respectively. Air medium provided a total energy input of 11.6 MJ compared to N_2. While the SMER and SEC values of fig drying in air medium are 0,06 kg_{water}/MJ and 16,67 MJ/kg, respectively, these values are 0,07 kg_{water}/MJ and 14,29 MJ/kg in N_2.

Aktaş et al. investigated the drying properties, and energy analysis of mint leaves in a new cylindrical drying chamber (Figure 5b) at low drying air temperature [42]. The dryer given in Figure 5a consists of a heat recovery unit, an air source heat pump system, and a proportional temperature control system. The experiments were carried out at 2, 2.5, and 3 m/s air speed and 35℃ cabin inlet air temperature. Samples were dried from 9 $g_{water}/g_{drymatter}$ to 0.1 $g_{water}/g_{drymatter}$. In the drying chamber design, three intertwined stainless steels are used in a circular form. Thus, this design provided a homogeneous airflow and prevented light samples such as mint leaves from spreading over the drying system. An energy-saving of 48% was achieved with the heat recovery unit. Liu et al. designed an air source heat pump dryer for drying food and made its thermal analysis [43]. The authors used SMER and MER as performance indicators to investigate the impact of environmental factors and hot air cycling on heat pump drying. Garlic of 3 mm thickness dried from 66.714% (w.b.) to 10%. Open and semi-open loop HPD was significantly affected by ambient temperature and humidity. The closed-loop HPD, on the other hand, was affected by the by-pass air ratio.

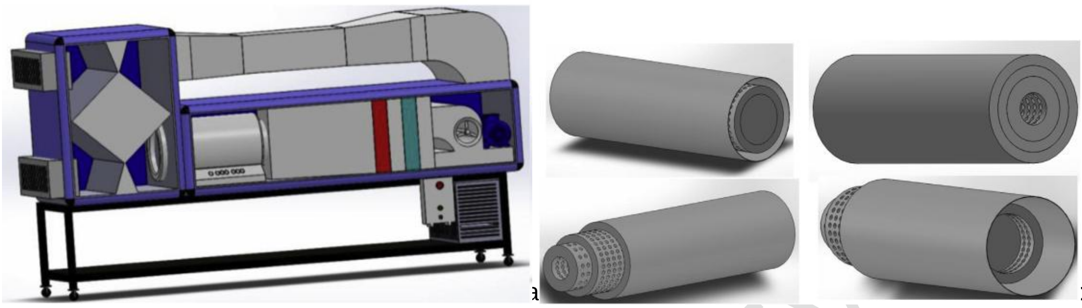

Fig. 5. (a) Air sourced heat pump dryer, (b) detailed view of the drying chamber [42]

Hii et al. presented the kinetics of heat pump drying of cocoa beans under cascade drying conditions and analysis of heat and mass transfer using 3-D computer simulation [44]. The samples were dried at constant temperature (56℃), stepped temperature (30.7-43.6-56.9℃), and gradually low temperature (54.9-43.9℃). The shrinkage factor is included in the mass and heat transfer models. The outcomes from the bean temperature profiles showed an excellent agreement between the experimental and simulation data, with mean relative errors less than 5%. Taşeri et al. dried grape pomace at various air velocities (1.5, 2, and 2.5 m/s) and 45℃ drying air temperature in an open-loop heat pump dryer and a laboratory type closed loop heat pump dryer for control purposes [45]. In open-loop HPD, drying air velocity had some effect on drying time. However, the change in drying air velocity at the same temperature did not significantly impact on power consumption. Compared to closed-loop HPD, the energy consumption of open-loop HPD is reduced by up to 51%. In open-loop HPD, a 69% reduction in drying time was monitored when the air velocity increased from 1.5 to 2.5 m/s.

Singh et al. simulated food quality and performance of a rack-type open-loop heat pump dryer using GWP working fluid (R600a, R290, R32, R123yf, and R152a) to dry bananas and carrots [46]. An experiment was conducted with a heat pump dryer using R134a for model validation. The impacts of sample moisture content and drying time on the system's COP, MER, SMER, SEC, drying efficiency, product water activity, exergy efficiency and destruction were investigated. This study revealed that R152a could be a potential choice for heat pump dryers when, personal safety (low flammability), performances, and environmental safety (low GWP) are considered. Shen et al. designed and experimented with an air source heat pump operating in procedures alternating between a cascade and single cycle to meet the heating demand at various ambient temperatures [47]. R22 and R134a are used as refrigerant. When the heat pump is operated at the design condition 20℃ for single stage and 0℃ for the cascade cycle, the supply air temperature meets the drying demand (70℃). With the increase in the ambient temperature, supply air temperature, electrical power, and heating capacity increased in both modes.

In some studies, the authors resorted to measuring the heat pump dryer's performance in comparison with other drying methods. Detailed information about some of these studies is summarized below. Yuan et al. developed a new partially open loop heat pump dryer with a unit room (HPDU) (Figure 6a) [48]. The unit room is designed to allow the return air to mix with the ambient air. Thus, the effect of ambient air on system performance will be reduced while thermal efficiency will be maintained. In the study, the system's characteristics under distinct ambient conditions and by-pass factor were examined. The energy profit of HDPU was measured through a comparative study with a closed-loop heat pump dryer (CHPD) (Figure 6b). Compared to CHPD, the COP of HDDPU increased by up to 39.56%.

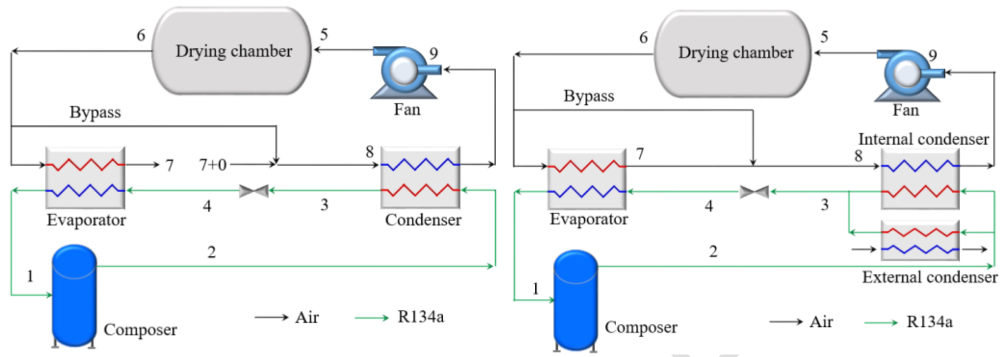

Fig. 6. Schematic representation of (a)unit room-HPD, (b) closed-loop HPD [48]

Hasibuan et al. compared the performance of solar-assisted heat pump dryer (SAHPD) (Figure 7b) with that of heat pump dryer (HPD) (Figure 7a) for Curcuma xant. Roxb. drying [49]. For HPD and SAHPD, the mean temperature-relative humidity value of 49.2℃-26.5% and 57.7℃-19.8%, respectively, HPD and SAHPD dried the samples from 30.7 kg to 7.85 kg in 10.5 and 8 h, respectively. The Curcuma's moisture was decreased from 3.167 (d.b.) to 0.065 at the drying airflow rate of 0.121 kg/s. SAHPD reduced drying time by 24% compared to HPD. For SAHPD and HPD, the drying rate and SEC are 1.36 kg/h and 1.05 kg/h and 2.07 kWh/kg and 1.17 kWh/kg, respectively. SMER and drying thermal efficiency are 0.521 kg/kWh and 0.931 kg/kWh and 34.3% and 61%, respectively. The moisture removal efficiency and COP values for HPD and SAHPD are %57.5 and %59.2 and 4.03, and 4.35, respectively. Yahya et al. compared the performance solar assisted heat pump (SAHPD) and solar dryer (SD) for drying cassava chips [50]. SAHPD and SD reduced the mass of cassava from 30.8 kg to 17.4 kg (from 61% to 10.5% (w.b.) in 13 and 9 h, respectively, at an average temperature of 40-45℃. The mean thermal efficiency of SAHPD and SD is 30.9 and 25.65%, respectively. SMER and drying rate are 0.38 kg/kWh and 1.33 kg/h for SD, and these values are 0.47 kg/kWh and 1.93 kg/h for SAHPD, respectively. The COPHP ranged from 3.23 to 3.47.

Wang et al. proposed a heat pump dryer (HPD) based on the production process of hawthorn cake [51]. The authors compared the experimental drying curves of hawthorn cake in HPD with those of conventional hot air drying. Higher drying temperature provided faster drying. However, in the first step of the heat pump drying operation, the moisture content of the hawthorn cake was not sensitive to the drying temperature, so a lower drying air temperature was required to obtain a higher COP from the heat pump. Aktaş et al. aimed to develop an infrared dryer (IRD)and heat pump dryer (HPD) (Figure 8), to analyze the comparative empirical analyzes of these two procedures, to examine drying kinetics of 15 mm thick stale bread and the effectiveness of the dryer on the testing kinetics of stale breads [52]. The highest COP of the whole heat pump system was detected as 3.7, and the drying efficiencies of the HPD and IRD systems were determined as 25% and 39%, respectively. Compared to HPD, the IRD system has reduced the drying time by up to 69% and the system's energy consumption by 43.2%.

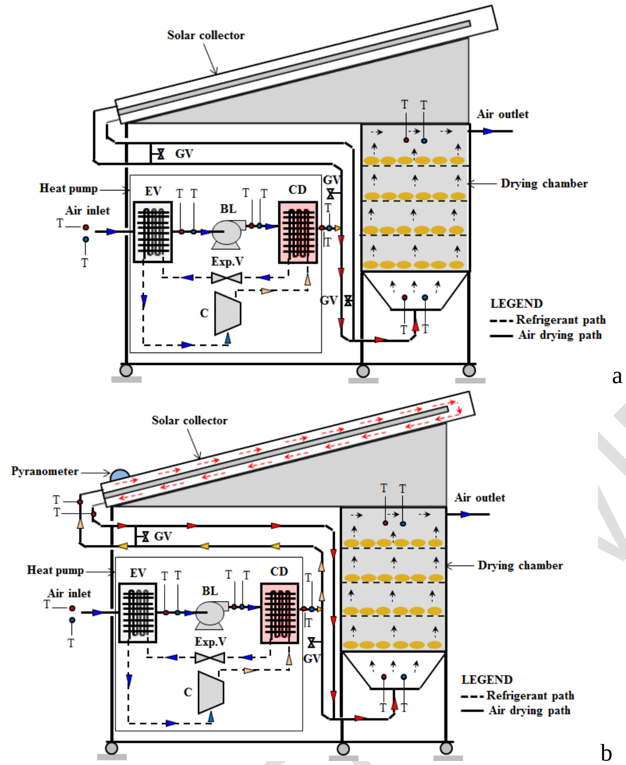

Fig. 7. Schematic representation of (a) HPD, (b) SAHP [49]

C:Compressor, BL:Blower, CD:Condenser, GV:Gate Valve, EV:Evaporator, T:Temperature Bulb, Exp. V:Expansion Valve

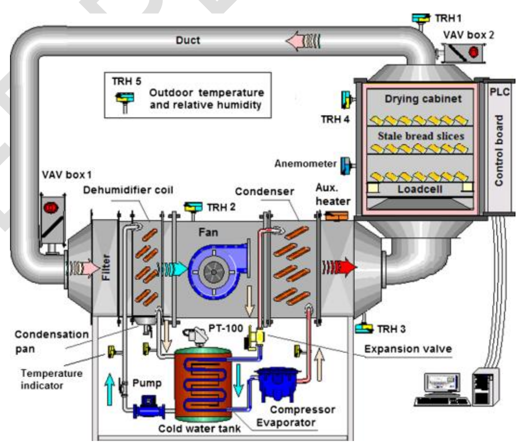

Fig. 8. Closed-loop heat pump dryer system [52]

TeGrotenhuis et al. used the computational modeling method to design a hybrid heat pump tumble dryer with 50% efficiency [53]. It has been stated that this model consist of the different stages of a drying cycle, from warming up to constant drying rate and decreasing drying rate stages, and finishing with a cooling stage. Gataric and Lorbek, investigated the performance of a domestic heat pump tumble dryer with R134a by using R450a [54]. Novak et al. evaluated the effect of various drum speeds and load masses on the performance criterions of a domestic heat pump drum dryer [55]. Holtkötter et al. focused on rapid-control-prototyping (RCP) technology to validate innovative heating concepts for heat pump tumble dryers [56].

3.2. Solar Assisted Heat Pump Dryer Performance Evaluation

The most critical disadvantage of solar drying is that the drying process cannot be done continuously. Solar-assisted heat pump dryers are recommended to both prevent the problem and increase the drying performance. This is an application in which solar collectors and heat pump dryers are integrated. This application is generally divided into two as conventional and direct solar assisted heat pump dryers. In the conventional application, the solar collector is a separate element in the system, while in the direct application, the solar collector is used as the evaporator of the heat pump dryer. That is, the working fluid in the heat pump circuit evaporates directly in the solar collector. The applications generally expressed in both of these groups can be arranged in different ways according to the purpose to be applied. There are many studies in the literature on this drying method. Some of the selected studies from the literature are summarized as given below.

Hawlader et al. designed, manufactured, and tested a water heater and solar assisted heat pump dryer [57]. The drying system comprise an evaporator, variable speed reciprocating compressor, air cooled condenser, auxiliary heater, storage tank, drying chamber, blower, and air collector. Some components can be isolated in the drying system depending on the weather conditions and utilization. A simulation program was developed in Fortran language to assess the system's performance and the effect of distinct variables. Performance parameters are solar fraction and COP with and without water heater. COP values acquired from experiment and simulation are 5 and 7, respectively, and solar fraction values are 0.61 and 0.65, respectively. Fadhel et al. designed and manufactured a solar assisted chemical heat pump dryer and tested the system's performance under the meteorological conditions of Malaysia [58]. As shown in Figures 9a and 9b, the drying system include a vacuum tube solar collector, solid-gas chemical heat pump, storage tank, and drying chamber. The reaction used in the heat pump is $CaCl_2$-NH_3. A simulation was developed to compare the results from the experiments. The chemical heat pump's COP in simulation and experiment is 2.2 and 2, respectively. Any energy reduction in the condenser as a result of the reduction in radiation from the sun reduced the COP and drying efficiency of the chemical heat pump.

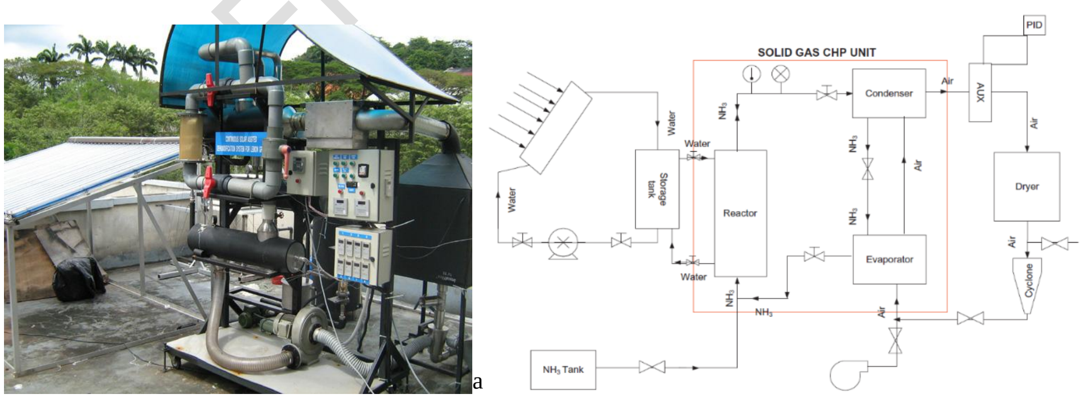

Fig. 9. (a) Experimental setup photo, (b) schematic drawing of solar assisted chemical HPD [58]

Li et al. proposed a new in-store drying system to reduce electricity consumption and take full benefit of solar energy [59]. The authors produced a prototype and conducted drying tests. Experimental data were compared with outcomes from a mathematical simulation. The solar assisted heat pump drying system has enhanced the performance of the in-store drying operation. The authors improved the uniformity of grain moisture content and drying rate. Rahman et al. presented the economic optimization study of the solar-assisted heat pump system's air-heated collector and evaporator area [60]. The authors performed a financial analysis based on the determination of optimum variables and payback period using a simulation program in the FORTRAN language. The payback period of the system was calculated to be 4 years.

Şevik et al. suggested simple and cost-effective solar assisted heat pump (SAHP) system with a flat plate collector and water source heat pump [61]. The drying of mushrooms in SAHP was investigated experimentally. Solar energy (SE) and heat pump (HP) systems were used together and separately in the experiments. Relative humidity, drying air temperature, product weight, etc., were observed using PLC in different scenarios. They dried the mushrooms at a mass flow rate of 310 kg/h and at 45 and 55°C drying air temperature from 13.24 $g_{water}/g_{drymatter}$ to 0.07 $g_{water}/g_{drymatter}$. Mushrooms were dried in SE, HP, and SAHP drying at 270-165 min. 250-220 min., and 230-190 min, respectively. COP_{SYS} is in the range of 2.1 to 3.1. The energy usage rate ranged from 0.42 to 0.66, and the SMER value ranged between 0,26-0,92 kg/kWh. Mohanraj investigated the energy performance of a solar-ambient hybrid source heat pump dryer (SAHSHPD) (Figure 10) for drying copra in hot-humid weather conditions [62]. Standard energy performance criterions such as condenser heat capacity, COP, SMER were evaluated. The $COP_{SAHSHPD}$ varied between 2.31-2.77, and the condenser heating capacity ranged between 2.9-3.75 kW. SMER is 0.79 kg/kWh. The copra on the bottom and top shelves of the drying room was dried in 40 h.

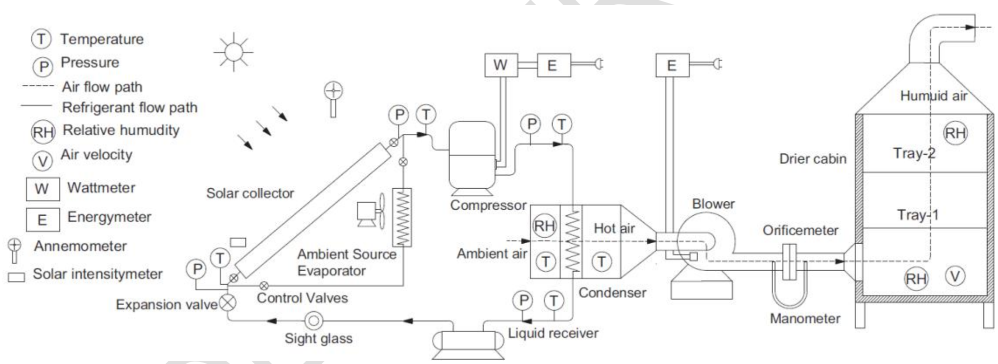

Fig. 10. Schematic drawn of solar-ambient hybrid sourced heat pump dryer [62]

Singh et al. developed a new compact size convective batch type solar-infrared assisted heat pump dryer (Figure 11a) and experimentally investigated the closed-loop drying of banana chips [13]. The performance of four different operating process: simple heat pump dryer, solar-assisted heat pump dryer, infrared assisted heat pump dryer, and solar infrared assisted heat pump dryer were compared. The impacts of drying time and sample moisture on energetic and exergetic performance parameters were investigated. At a drying air velocity of 0.8 m/s, the sample's moisture was reduced from 83.8% to 11.5%. Qiu et al. installed a new solar assisted heat pump drying system with thermal storage and heat recovery [63]. The authors investigated the impact of different economic factors on the payback period. They have integrated a condenser and evaporator in the drying chamber and added a water storage tank to the system to improve the use of solar energy and recover heat effectively (Figure 11b). In the experiments performed in SAHPD mode, the $COP_{dryingsystem}$ changed from 3.21 to 3.49. In addition, SAHPD has saved 40.53% in energy consumption in terms of thermal storage and heat recovery. The payback period of drying radishes, peppers, and mushrooms in the system's life is 6, 4, and 2 years, respectively.

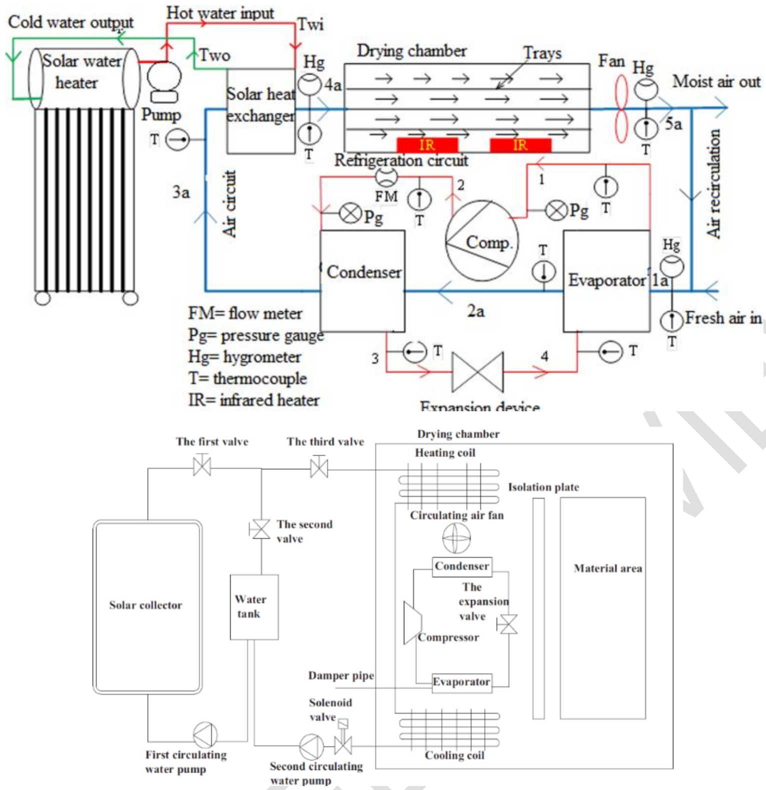

Fig. 11. Schematic drawn of (a) convective batch-type solar-infrared assisted HPD [12], (b) heat recovery and heat storage SAHPD [63]

Şevik shared the experimental results of a drying system for continuous drying of different agricultural products in various climatic conditions [64]. While the heat requirement of the drying system is met with a new type of double-pass solar air collector (DPSAC) and heat pump, the electricity need of the system is met with a PV panel. In this study, the author aimed to keep the drying air temperature constant with PID, to acquire the temperature in the drying chamber homogeneously, to discover the effect of PID control on the DPSAC and to analyze the drying of different products at 50℃ with varying drying airflow. The COP of the whole system for tomatoes, strawberries, mint, and parsley was 1.96, 2.27, 2.28, and 2.17, respectively. The mean thermal efficiency of DPSAC varied between 16-79%. The SMER of the whole system ranged between 0.03 kg/kWh and 0.46 kg/kWh. The energy utilization rate is in the range of 0,19 to 0.48.

3.2. Exergy Analysis Evaluation

For the last few decades, exergy analysis based on the second law of thermodynamics as well as first law analysis of thermodynamics has been one of the most used methods to evaluate the performance of thermal systems. Namely, exergy analysis provides excellent convenience for researchers in design and optimization processes as well as evaluating the performance of thermal systems [65]. The exergy expression, which is generally defined as the maximum useful work, must undergo a process in which a system interacting with the environment becomes equilibrium. Exergy analysis is a useful tool as it detects the location and severity of exergy destruction in the examined system [66,67]. When the studies in the literature are examined, it is seen that conventional exergy, advanced exergy, exergoeoconomic, etc., methods are used. The studies in the literature in which exergy analysis is used to assess the performance of heat pump dryers used in drying fruits, vegetables, plants, fish, meat, and clothes are given below in chronological order. Also, these studies are summarized in Table 2.

Hepbasli et al. designed and produced a heat pump dryer for drying plums and conducted drying experiments in the temperature range of 45-55℃ [68]. They evaluated the dryer's performance with all its components by exergoeconomic analysis based on exergy, cost, energy, and mass (EXCEM) procedure. As the drying air temperature increased, the R_{en} (Ratio of energy loss to the cost of capital) value decreased, and the R_{ex} (Ratio of exergy destruction to cost of capital) value increased. While R_{ex} and R_{en} values increased linearly with increasing temperature due to loss, R_{en} and R_{ex} values decreased in the compressor, unlike other components. Gungor et al. dried three aromatic and medicinal plants in a pilot-scale gas engine-driven heat pump dryer they designed and built at Ege University in Turkey [69]. Drying experiments were carried out at a speed of 1 m/s and an air temperature of 45℃. The dryer's performance was measured by exergy analysis. The most crucial component to increase system efficiency was the gas engine, followed by the heat exchanger and exhaust air. Sustainability index values were calculated for the system components. The expansion valve, gas engine, and drying channels accounted for more than 60% of the exergy in the system.

Gungor et al., in other study, applied the exergoeconomic analysis of the same drying system using the EXCEM method based on experimental data [70]. The authors discussed the performance of drying system components and identified important system components to increase system efficiency. In this study, an exhaustive parametric study was carried out to investigate the impact of different dead state temperatures on exergoeconomic performance parameters. Correlation between dead state temperatures and performance parameters has been developed. The increased dead sate temperature increased the exergy efficiency of the drying process and led to a decrease in R_{ex} values. Again, the same authors analyzed the same drying system, this time using conventional and advanced exergy procedure [71]. Avoidable and unavoidable exergy destruction, modified exergy efficiency, and exergy destruction rates were calculated for each system component. Except for the drying cabinet, evaporator, and compressor most of the exergy destruction of system components is avoidable, and these avoidable parts can be reduced with design improvements.

Erbay and Hepbasli investigated the performance of a pilot-scale air source heat pump food dryer with conventional and advanced exergoeconomic analysis and compared the results [72]. The contributions of the drying system components to the exergetic cost efficiency of the dryer were determined, and the impacts of changing the inlet drying air temperature were evaluated. It has been determined that the most critical system component is the heat recovery unit, followed by the condenser according to the potential to reduce the total cost of the entire system. The decreasing temperature increased drying cost performance. Erbay and Hepbasli applied advanced exergy analysis to assess the performance of each component of a ground source heat pump drying system used in food drying for the first time in the literature [73]. The results indicated that the most crucial system component in terms of design is the condenser. Inefficiencies in the compressor can be overcome, especially with structural improvements of the entire system and the remaining components. Also, the internal operating condition affected inefficiencies in system components other than the condenser and evaporator. Both the equipment design of the condenser and the evaporator and the interactions of system components have had a notable impact on inefficiencies.

Ganjehsarabi et al. performed exergy and exergoeconomic analysis of a heat pump tumble dryer using real thermodynamic and cost data [74]. Cotton fabric was dried in the experiments. Depending on the drying temperature and the mass flowrate of the air, the system performance and the costs of the components were investigated parametrically. Gungor et al. performed advanced exergoeconomic analysis to assess the performance with each component of a gas engine-driven heat pump drying system used for the first time in food drying [75]. The unavoidable part of the exergy destruction cost ratio in the system components was lower than the avoidable part. The most critical components with respect to the total avoidable costs are the drying channels, the expansion valve, and the condenser. Interior design changes played an important role in identifying the cost of each component.

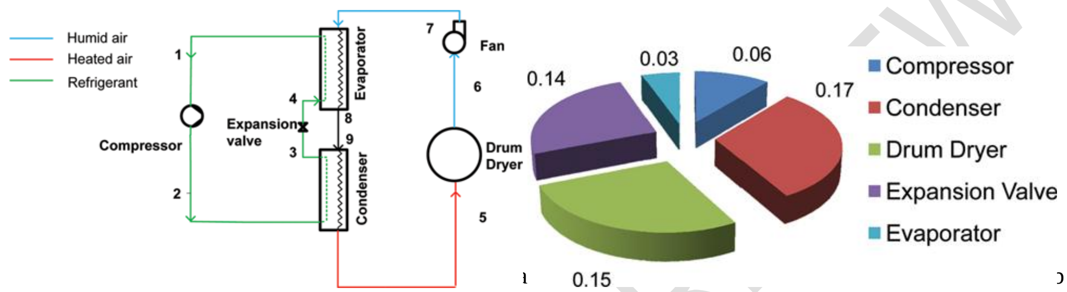

Fig. 12. (a) Schematic drawn of the experimental setup, (b) exergy destruction cost rate in system components [74]

Erbay and Hepbasli, for the first time in the literature, discussed the exergoeonomic analysis of the ground source heat pump dryer (GSHPD) with the specific exergy cost procedure [76]. The authors investigated the variations of dead state temperature and exergetic and exergoeconomic performance parameters and compared them with literature results. The heat exchangers in the GSHPD are affected by the variation of the dead state temperature. The increase in the dead state temperature caused a decrease in the exergy efficiency of the system components. The total cost incurred in the evaporator increased importantly with the ascend in the dead state temperature. Aktaş et al. have developed a hybrid drying system that merges all the superiorities of different drying techniques [77]. The authors aimed to investigate the drying kinetics of grated carrot, to determine the energy and exergy efficiency of the dryer and compared the experimental outcomes of infrared assisted heat pump dryer (IRRAHPD) and a heat pump dryer (HPD). The samples were dried at a drying air velocity of 0.5 m/s at 45 and 50℃. The samples were dried from 7.06 $g_{water}/g_{drymatter}$ (d.b.) to 0.14 $g_{water}/g_{drymatter}$.

Brandt et al. investigated the R744 as an alternative for use in small commercial tumble dryers [78]. The authors presented an exergy analysis for the assessment of different system topologies. Possible reductions in exergy destruction due to throttling losses have been estimated. Erbay and Hepbasli implemented advanced exergoeconomic analysis to a ground source heat pump drying system [79]. Cost performance and thermodynamic inefficiencies of system components are analyzed in parts. Advanced exergoeconomic analysis results were compared with conventional exergoeconomic analysis outcomes. The avoidable investment cost is considerably lower than the avoidable destruction cost. The most crucial system components in terms of reducing costs are the drying channel and the condenser. In addition, it is possible to decrease 34.6% of the total costs when drying channel and condenser focused improvement strategies are developed.

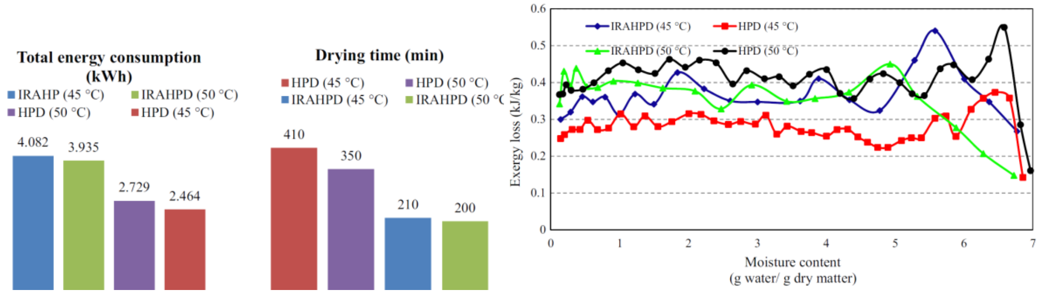

Fig. 13. In the different working mode (a) drying time and energy consumption comparison (b) change in exergy loss with moisture content [77]

Singh et al. developed batch-type solar assisted heat pump dryer (SAHPD) for closed-loop drying of banana chips in both simple heat pump dryer (HPD) and SAHPD modes [80]. The impact of drying time on economic, energy, and exergoeconomic performance parameters was investigated. Samples were dried from an initial moisture level of 83.5% to 11.5% at a drying air speed of 1 m/s. SAHPD's payback period over HPD is 46 months. The lowest exergoeconomic factor for HPD and SAHPD was obtained in the expansion valve with 0.1395 and 0.2053, respectively. The authors stated that SAHPD was better than HPD. Singh et al. this time designed and manufactured convective type closed-loop solar assisted heat pump dryer (SAHPD) to conduct experimental research for basic HPD and SAHPD modes [81]. Thermodynamic, economic and exergoeconomic, performance parameters were compared for each drying mode. Both energy and exergy efficiency was higher for SAHPD. In addition, COP, moisture removal from the product, drying rate, and SMER criteria were higher for SAHPD compared to HPD. Further improvements are needed for the expansion device and evaporator based on the exergoeconomic factor.

Table 2. Some studies selected from the literature on the application of exergy analysis to heat pump dryers

Ref.	Product	Dryer	Methods	Highlight outputs
[68]	Plum	Conveyor HPD	EXCEM	Exergy efficiency: 72.72-75.66% R_{ex}:1.668-2.063 W/$, R_{en}:6.258-5.749 W/$ COP_{HP}:2.56-2.81
[69]	Medicinal and aromatic plants	GEHPD	Exergy analysis	Exergy efficiency for HP:77.68-79.21% for GEHPU: 39.26-43.24% for drying chamber: 81.29-81.56% for whole system: 48.24-51.28%
[70]	Medicinal and aromatic plants	GEHPD	EXCEM	Increasing the dead state temperature increased the exergy efficiency of the drying process an decreased the Rex value
[71]	Medicinal and aromatic plants	GEHPD	Conventional and advanced exergy analysis	Conventional exergy efficiency for HP: 82.51-85,11% and for GEHPD:79.71-81.66%, Advanced exergy efficiency for HP:85.7-89.26% and for GEHPD:84.5-86%
[72]	Plum	ASHPD	Conventional and advanced exergoeconomic analysis	The increase in drying air inlet temperature created low cost and high development potential.
[73]	Daphne leaves	GSHPD	Conventional and advanced exergy analysis	Conventional and advanced exergy efficiencies of the drying system are 77.05% and 93.5%, respectively.

Ref.	Product	Dryer	Methods	Highlight outputs
[74]	Cotton fabric	HPTD	Exergy and exergoeconomic analysis	The exergy efficiency of HP and HPTD are 0.07 and 0.11, respectively. R_{ex} varied depending on dying airflow and temperature
[75]	Medicinal and aromatic plants	GEHPD	Advanced exergoeconomic analysis	The development potential of the exergy destruction cost of the whole system is 74%. The avoidable part of the exergy destruction costs of the system components is higher than the unavoidable part
[76]	Daphne leaves	GSHPD	Specific exergy cost method	The increase in the dead state temperature caused a decrease in the exergy efficiency of the system components.
[77]	Grated carrot	HPD/ IRAHPD	Energy and exergy analysis	SEC:10.33/17.39 MJ/kg Exergy efficiency:48-50%/ 58-65% IRAPHD reduced drying time by 48.8%
[79]	Daphne leaves	GSHPD	Conventional and advanced exergoeconomic analysis	68.6% of the total exergy destruction cost is avoidable. The condenser and drying duct account for 81.7% of the total avoidable exergy destruction cost.
[80]	Banana chips	HPD/ SAHPD	Energy, economic and exergoeconomic analysis	TEC:2.75/1.91 kWh. Exergy dest.:0.431/0.638 kW exergy dest. cost:0.1185/0.1386 $/h. Exergoeconomic factor: 0.1395/0.2053
[81]	Banana chips	HPD/ SAHPD	Thermodynamic, economic, and exergoeconomic analysis	Lowest exergoeconomic factor: 0.1335/0.2003 (for expans. valve). TEC:2.77/1.94 kW. Exergy efficiency SAHPD>HPD. Payback period 3.9 years.
[82]	Tomatoes	SD/HPD	Exergoeconomic analysis	Exergy efficiency: 75.52/72.49%, min. exergy destruction cost:0.0044/0.06$/h exergoeconomic factor: 0.514/0.045

4. CONCLUSION

In this study, studies in the literature on heat pump dryers were examined. It has been revealed how the researches carried out in this field in recent years has contributed to the literature and how the heat pump dryers have improved. In these studies, the performance of heat pump dryers in drying products such as various vegetables, fruits, medicinal and aromatic plants, meat, fish, and clothes was investigated. In these studies, moisture extraction rate, energy consumption amount, specific moisture extraction rate, moisture evaporation efficiency, COP, etc. evaluated as performance criteria. In order to increase efficiency and reduce drying time in heat pump dryers, it is supported by heat sources such as a solar, infrared, and electric heater. In some studies, comparative experimental studies have demonstrated the performance of these dryers.

Heat pump dryers have been further evaluated by exergy analysis. In particular, exergy analysis helps to reduce irreversibility and increase efficiency [83]. In this framework, studies using exergy analysis have an important place in the literature. When the studies are examined, in addition to conventional and advanced exergy analysis, exergoeconomic analysis in which exergy analysis and economic parameters are integrated, and moreover, advanced exergoeconomic analysis methods are used. In some studies, the results of these methods have been compared. Studies show that heat pump dryers are an efficient drying system. Beyond that, especially solar assisted heat pump dryers have had better performance indicators than conventional heat pump dryers. Heat pump dryers consume less energy than industrial drying systems and can dry faster than solar dryers. In addition, the factors affecting drying can be kept under control. Heat pump dryers are available in the market as economical and high-performance devices, especially for drying clothing. Heat pump food dryers, on the other hand, have a very limited place in the market. In order to overcome this situation, development processes should be continued with much more scientific studies.

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