Review Article

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

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ABSTRACT

Heat pump dryers provide tremendous advantages in the drying sector, an energy-intensive process. Studies on heat pump dryers for many years still maintain their popularity today. The presented study deals with the developments in heat pump dryers in recent years. Only 82 of the studies that contributed to the literature between 1997 and 2022 were examined in this framework. This study firstly focused on studies examining the performance of heat pump dryers used in food drying, mainly in which ambient air is used as a source. In the following, this review summarizes the results from studies on chemical heat pump dryers and drum heat pump dryers for drying clothes. This review also covers applications that integrate solar and infrared, which increase the efficiency of heat pump dryers, and studies using exergy analysis. The examined studies were evaluated in terms of performance parameters such as coefficient of performance, specific moisture extraction rate, drying time, exergy efficiency, and destruction. This review study shows that improvements in heat pump dryers will reduce drying time and operating costs. 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

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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 using these energy resources. Using and disseminating more effective and innovative drying technologies has a key role in this context.

Solar energy is mainly preferred after fossil-based energy sources in drying. However, the inability of solar dryers to perform drying during the night and on 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 to 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 a wide range of products.

This review study discusses recent developments and studies contributing to the literature about heat pump dryers. 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, and economic aspects. The performance of the heat pump dryers in these evaluated studies was examined in terms of drying rate, moisture extraction rate (MER), specific energy consumption (SEC), specific moisture extraction rate (SMER), coefficient of performance (COP), total energy consumption (TEC), exergy destruction and efficiency, pick-up efficiency, etc. (Fig. 1).

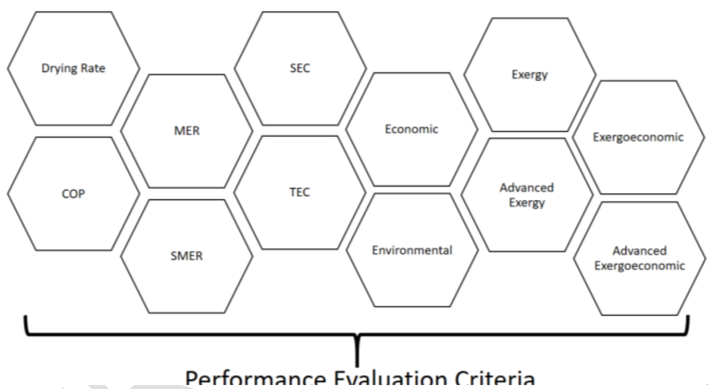

Fig. 1. Performance evaluation criteria of heat pump dryers examined in this study

2. HEAT PUMP DRYER SYSTEMS

The most crucial purpose of 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 meager, 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.

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2.1. Working Principle of Heat Pump Dryers

Heat pump dryer (HPD) systems can generally be expressed as the integration of the drying chamber and the heat pump. The 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 Fig. 2a, an open-loop heat pump drying system has a drying air and a working fluid 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 (Fig. 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.

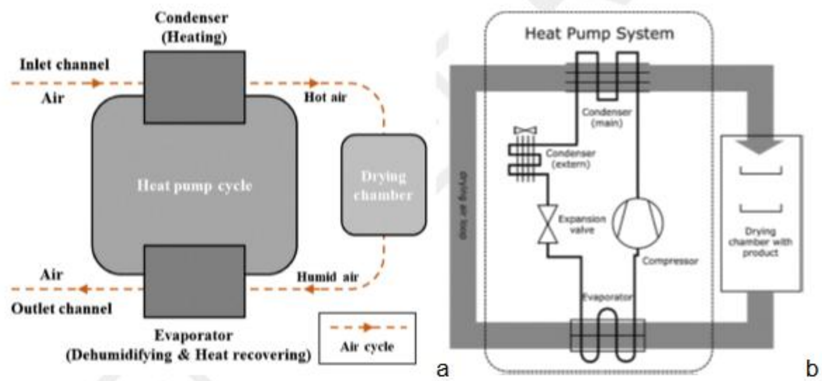

Fig. 2. Schematic representation of (a) Open-loop HPD [10], (b) closed-loop HPD [11]

2.2. Classification of heat pump dryers

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

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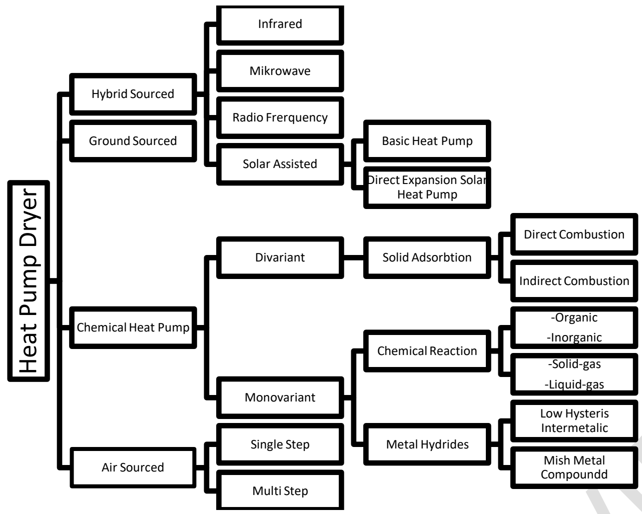

Fig. 3. Classification of heat pump dryers [6]

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, the 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 investigating the performance of heat pump dryers selected from the literature is presented in mini-summaries.

Wongwises et al. designed, manufactured, and measured a heat pump dryer's performance [32]. 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 fundamental parameters affecting the performance and drying speed of the system were determined. Fatouh et al. manufactured a heat pump dryer to experimentally analyze the drying characteristics of jew's mallow, parsley, and spearmint [33]. 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 was achieved at 55℃, 2.7 m/s drying condition, and 28 kg/m^2 dryer surface load. Drying temperature and surface load significantly affected specific energy consumption and dryer efficiency. Phoungchandang ve Saentaweesuk measured desorption isotherms for sliced ginger [34]. They performed tray and heat pump moisture-free drying in one- and two-stage trials. They also investigated the quality of the samples by parameters such as color and rehydration. 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.	Final	Drying Conditions	Drying	Highlight Outputs	Ref.

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	Moist.	Moist.		Time		
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]

**Dry basis, **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 samples with an initial moisture content of 32% (d.b.) were dried in a heat pump dryer under four drying air (40-70℃), at a surface velocity of 0,4 m/s, at constant 60% by-pass air. While the inert gases did not affect the drying rate, but they increased with temperature change. Moisture rates were compared between seven thin layer models during the drying operation. The one-step regression method determined the impact of drying temperatures on the coefficients of the best humidity model. The most compatible model illustrating the drying behavior was Midilli.

Hii et al. explored 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 and increased with decreasing moisture content. Shi et al. discussed the drying quality and kinetics properties of yacon in a heat pump dryer at different dying temperatures (from 5℃ to 45℃) and velocities (from 0.5 to 2 m/s) [37]. The drying time was reduced with increasing air velocity and temperature. Eight different thin-layer models were used to 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. tested the desiccant wheel system integrated with a high-temperature heat pump and associated air conditioning unit to overcome the trouble of high energy consumption, schematically drawn in Fig. 4 [38]. The authors stated that the regeneration airflow rate, ambient temperature, and humidity greatly influence the heat pump's performance based on COP. The maximum COP_{HP} and COP_{HPS} were found at 2.26 and 2.08, respectively. Juan et al. investigated a heat pump dryer's performance for drying

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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 removed 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.

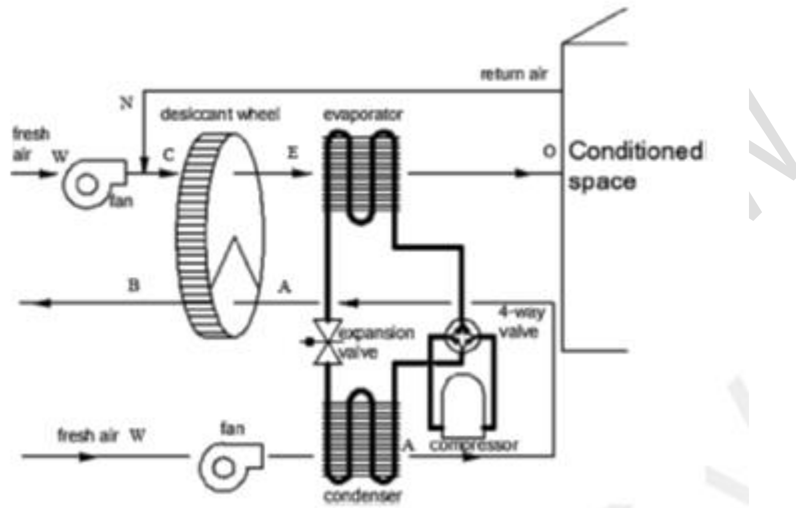

Fig. 4. High-temperature heat pump dryer and desiccant wheel [38]

Yamankaradeniz et al. designed, built, and tested a circulating HPD system under steady-state and transient conditions [40]. The authors investigated the impact of by-pass air ratio (BAR) on system performance and the steady-state SMER value parameters. The effects of drying temperature and relative humidity changes on time-dependent system parameters were investigated. The system parameters did not change up to 40% of BAR. The SMER and COPsyst varied between 1.2-1.4 and 2.8-3.3, respectively, depending on the BAR. During the drying process, COP and SMER values decreased depending on time. Chapchaimoh et al. discussed the energy consumption and performance of a closed system HPD 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 of mint leaves at low drying temperature and designed a drying chamber in the cylindrical form [42]. The dryer given in Fig. 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 air velocities range of 2-3 m/s and drying temperature of 35℃. 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 (Fig. 5b). 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 HPD for drying food and made its thermal analysis [43]. The authors used SMER and MER as performance indicators to investigate the impact of ambient humidity and temperature and hot air cycling on heat pump drying. Garlic of 3 mm thickness dried from 66.714% (w.b.) to 10%. Environmental conditions significantly impacted Semi-open and open-loop HPD. The closed-loop HPD, on the other hand, was affected by the by-pass air ratio.

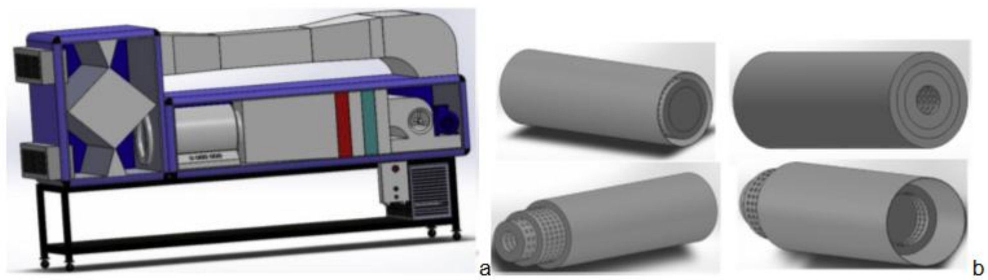

Fig. 5. (a) Air sourced heat pump dryer, (b) detailed view of the drying chamber [42]

Hii et al. compared the moisture ratio and temperature profiles of cocoa beans dried in an HPD with simulation results [44]. The samples were dried at 56℃ (constant), 30.7-43.6-56.9℃ (stepped), and 54.9-43.9℃ (gradually low temperature). The shrinkage factor is included in the mass and heat transfer models. The outcomes of the bean temperature profiles demonstrated a magnificent agreement between the experimental and simulation outcomes, with mean relative errors of less than 5%. Taşeri et al. dried grape pomace in an open-loop HPD at various air velocities (ranged 1.5-2.5 m/s) and 45℃ drying temperature to determine the drying characteristics and bioactive properties of samples [45]. Also, they compared their results with those of closed-loop HPD. In open-loop HPD, drying air velocity had some effect on drying time. However, the alteration of air velocity at the same temperature did not significantly impact 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 raised from 1.5 to 2.5 m/s.

Singh et al. simulated the food quality and effectiveness of a rack-type open-loop HPD 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 showed that the performance of R32 and R152a is more successful for HPD applications than others. Shen et al. presented the experimental results of the HPD operating in single-stage and cascade cycle operating modes that vary according to environment temperatures [47]. R22 and R134a are used as the refrigerant. These modes of operation vary to achieve targeted efficiency and heat generation. The results showed that the air temperature provided by the single-stage was lower than that of the cascade cycle at the same environmental temperature. Since the heating capacity of the cascade cycle is higher, it consumes more electricity than the single stage.

In some studies, the authors resorted to measuring the heat pump dryer's performance compared to other drying methods. Detailed information about some of these studies is summarized below. Yuan et al. validated the numerical analyzes of a partially open loop HPD integrated with a unit room with experiments performed on the closed-loop HPD [48]. As shown in Fig. 6, the unit room ensured control of the heat pump's efficient operation and

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reduced the effect of the environment air with the air mixture. Points a, b, c, and d gave temperature and humidity measurement points in this figure. Thus, the effect of ambient air on system performance will be reduced while thermal efficiency will be maintained. The study examined the system's characteristics under distinct ambient conditions and by-pass factors. Compared to CHPD, the COP of HDPU increased by up to 39.56%.

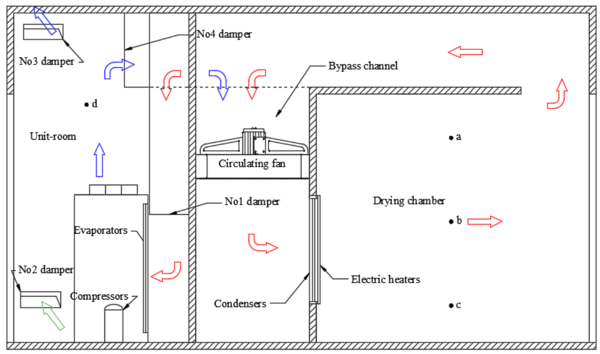

Fig. 6. Schematic representation of HPDU [48]

Hasibuan et al. compared the performance of a solar-assisted heat pump dryer (SAHPD) (Fig. 7b) with that of a heat pump dryer (HPD) (Fig. 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. When drying times are compared, SAHPD provided a 24% advantage over 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 efficiencies 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 rates 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 COP_{HP} 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 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 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 the drying kinetics of 15 mm thick stale bread and the effectiveness of the dryer on the testing kinetics of stale bread [52]. The highest COP_{sys} were detected as 3.7. The drying efficiencies of the HPD and IRD were determined as 25% and 39%, respectively. Compared to HPD, the IRD has reduced the drying time by up to 69% and the system's energy consumption by 43.2%.

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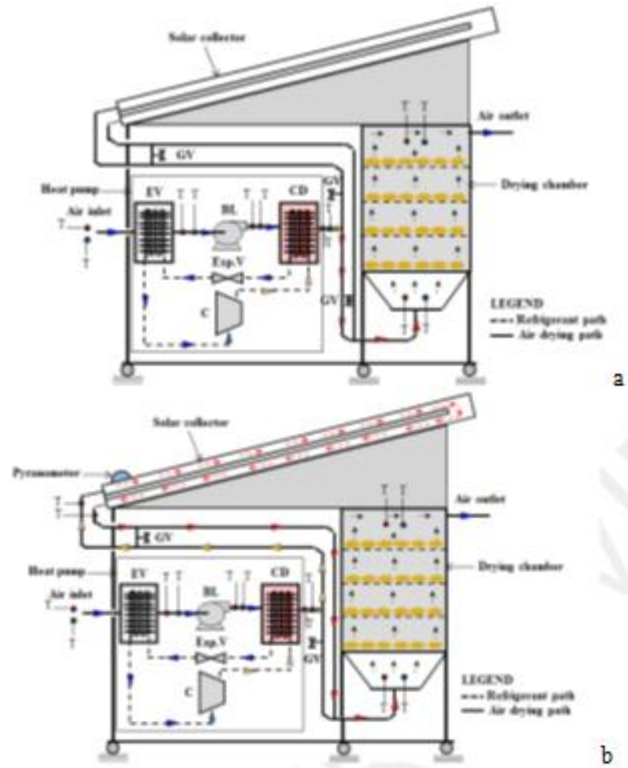

Fig. 7. Schematic representation of (a) HPD, (b) SAHP [49]

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

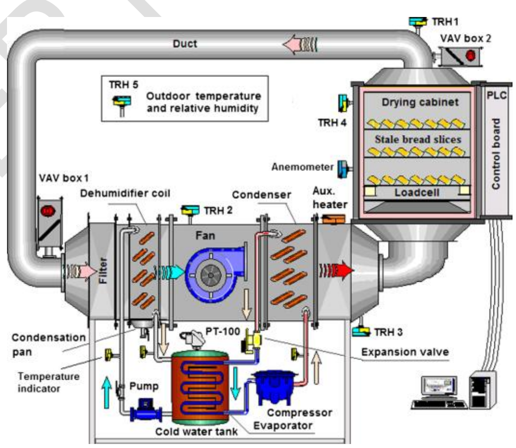

Fig. 8. Closed-loop heat pump dryer system [52]

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 consists 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, evaluated the

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performance of R450a used in a domestic heat pump tumble dryer with R134a [54]. Novak et al. evaluated the effect of various drum speeds and load masses on the effectiveness criteria of a domestic heat pump drum dryer [55]. Holtkötter et al. developed rapid-control-prototyping (RCP) technology to confirm original heating methods for heat pump tumble dryers [56].

3.2. Solar Assisted Heat Pump Dryer Performance Evaluation

The most critical drawback of solar drying is that the drying operation cannot be done continuously. Solar-assisted heat pump dryers are recommended to 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. The solar collector is a separate element in the system in the conventional application. In contrast, in the direct application, the solar collector is used as the evaporator of the heat pump dryer. The refrigerant 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. conducted a simulation to evaluate the performance of a water heater and solar-assisted HPD [57]. They performed experiments to verify this simulation. The drying system comprises an evaporator, variable speed reciprocating compressor, air-cooled condenser, auxiliary heater, storage tank, drying chamber, blower, and air collector. According to the meteorological conditions and utilization, some components can be isolated in the drying system. Performance parameters are solar fraction and COP with and without water heater. COP values acquired from the experiment and simulation are 5 and 7, respectively. And solar fraction values are 0.61 and 0.65, respectively. Fadhel et al. evaluated the performance of a solar-assisted chemical HPD under the meteorological conditions of Malaysia [58]. Fig. 9a and 9b show that the drying system includes a vacuum tube solar collector, solid-gas chemical heat pump, storage tank, and drying chamber. The heat pump used the $CaCl_2$-NH_3 chemical reaction. 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 caused by the reduction in radiation from the sun reduced the COP and drying efficiency of the chemical heat pump.

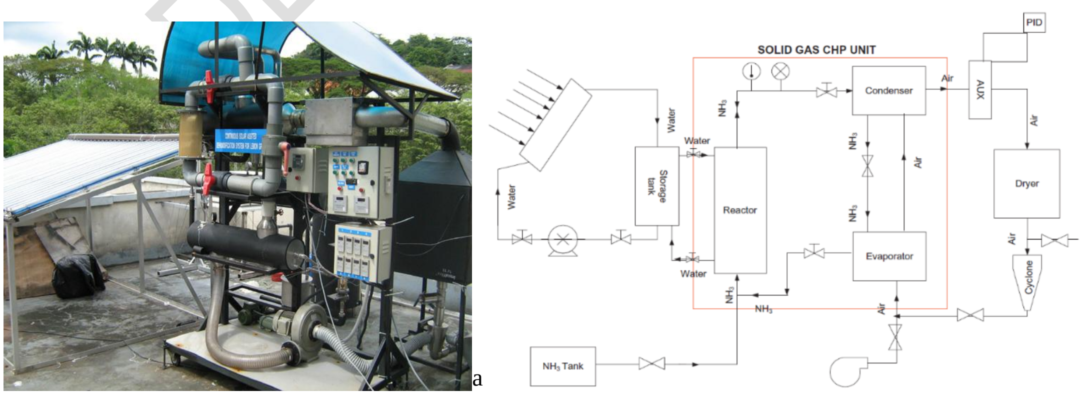

Fig. 9. (a) Experimental setup photo, (b) schematic drawing of solar assisted chemical HPD [58]

Li et al. proposed a new in-store drying system to reduce electricity consumption and benefit from solar energy [59]. The authors produced a prototype and conducted drying tests. Experimental results obtained from four operation modes were compared with those of mathematical simulation. The solar-assisted HPD system has enhanced the effectiveness of the in-store drying operation. Therefore, the authors improved the drying rate and uniformity of grain moisture content. Rahman et al. presented the new economic optimization method of the solar-assisted HPD system's air-heated collector and evaporator area [60]. The authors performed this new financial analysis based on the determination of optimum variables and payback period using a simulation program in the FORTRAN language. The discount and fuel inflation rates seriously affected the payback period of 4.37 years.

Şevik et al. suggested a drying system that allows drying with a solar-assisted HPD during daylight and an HPD at night [61]. The authors used solar energy (SE) and heat pump (HP) together and separately as energy sources 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 flowrate of 310 kg/h and 45 and 55°C drying temperatures from 13.24 $g_{water}/g_{drymatter}$ to 0.07 $g_{water}/g_{drymatter}$. Mushrooms were dried in SE, HP, and SAHP 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 SMER value ranged between 0,26-0,92 kg/kWh. Mohanraj investigated the effectiveness of a solar-ambient hybrid source heat pump dryer (SAHSHPD) for drying copra under hot-humid weather conditions [62]. As shown in Fig. 10, the ambient source evaporator and solar collector are connected parallel in the refrigerant circuit. That is, the refrigerant circulates inside the solar collector. 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 for 40 h.

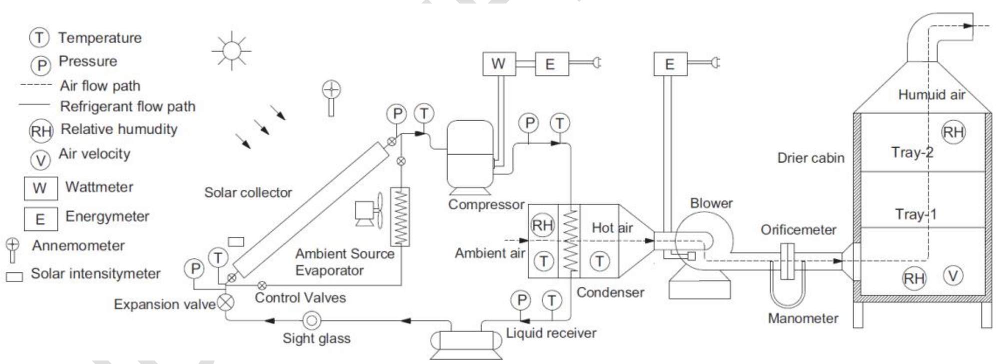

Fig. 10. Schematic drawing of solar-ambient hybrid sourced HPD [62]

Singh et al. compared the performance of the drying process in four different operating modes on a hybrid HPD system-assisted solar and infrared energy source [13]. The authors conducted the experiments in open and closed-loop conditions. As seen in Fig. 11a, the heat from the solar water heater and heat pump combines in a solar heat exchanger and enters the drying cabinet. Infrared heaters are located at the bottom of the shelves in the drying cabinet. Among the HPD, SAHPD, IAHPD, and SIAHPD operating modes, SAHPD was most successful in terms of SMER, while SIAHPD was most successful in terms of MER. Qiu et al. combined a solar-assisted HPD system with thermal storage and heat recovery [63]. Using a heat storage device, they aimed to continue the drying process during cloudy and night hours. As seen in Fig. 11b, the drying system consists of HPD and SD subsystems. Thus, drying was performed in HPD, SD, and SAHPD operating modes. The authors investigated the impact of different economic factors on the payback period. In the experiments performed in SAHPD mode, the COP_{syst} 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.

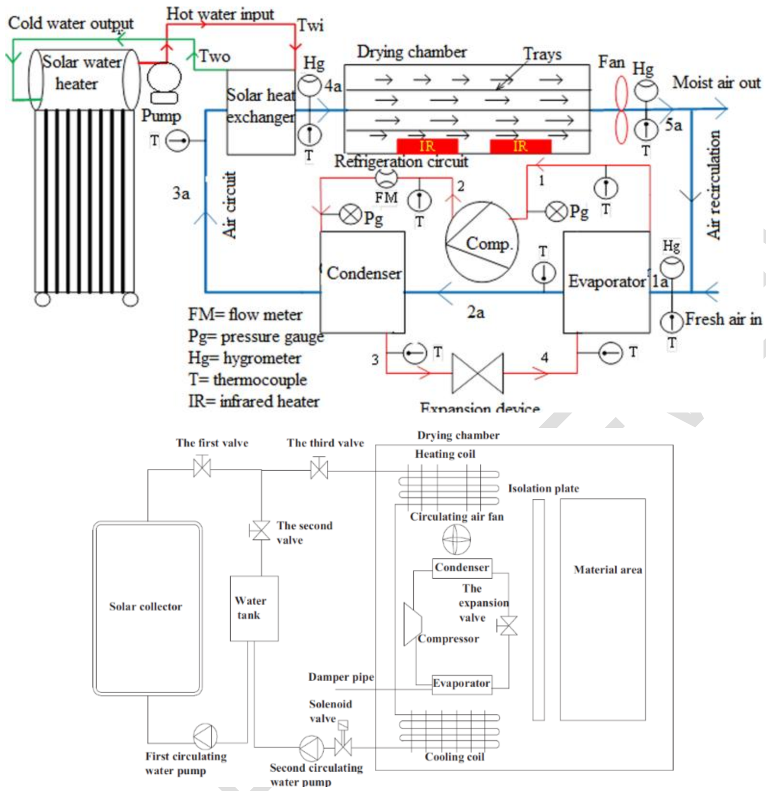

Fig. 11. Schematic drawing of (a) convective batch-type solar-infrared assisted HPD [13], (b) heat recovery and heat storage SAHPD [63]

Şevik shared the experimental results of an HPD system combined with a new type of double-pass solar air collector (DPSAC) [64]. The drying system described in this study operates in an open loop and thus differs from previous similar studies. The electricity need of the system is met with a PV panel. The author aimed to keep the drying temperature constant with PID. Also, the authors investigated the effect of PID on DPSAC. The COP_{sys} for tomatoes, strawberries, mint, and parsley were 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. The author stated that the efficiency could be increased with the heat recovery application in this system.

3.3. Exergy Analysis Evaluation

For the last few decades, exergy analysis based on the second law of thermodynamics as well as the 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 in evaluating the performance of thermal systems [65]. The exergy expression, 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 to detect 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. 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]. The drying process was carried out at an air velocity of 1 m/s and a drying 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. The authors calculated sustainability index values for each of 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 another study, applied the exergoeconomic analysis of the same drying system using the EXCEM method based on experimental data [70]. The authors discussed the effectiveness of components and identified important system components to increase system efficiency. They conducted a detailed parametric survey to determine the variation in exergoeconomic performance parameters according to different dead state temperatures. A 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 using conventional and advanced exergy procedures [71]. They calculated modified exergy destruction, modified exergy efficiency, and avoidable and unavoidable exergy destruction. The highest unavoidable exergy destruction values were obtained in the compressor, drying cabinet, and evaporator. The latent heat and drying airflow losses in the drying process have caused inefficiencies in the drying cabinet. Avoidable parts can be reduced with design improvements.

For the first time in the literature, advanced exergoeconomic analysis was applied to a pilot-scale air source heat pump dryer by Erbay and Hepbasli [72]. They investigated the exergetic cost-effectiveness and improvement potential of the system components. Also, this study investigated the effect of drying temperature change on exergoeconomic performance. It has been determined that the most critical system component is the heat recovery unit, the condenser, according to the potential to reduce the total cost of the entire system. As the temperature decreased, the drying cost performance increased. In another food drying study, Erbay and Hepbasli performed advanced exergy analysis on each ground source HPD system component for the first time in the literature [73]. They compared their results with conventional exergy analysis and investigated possible development possibilities of the components. The results indicated that the most crucial component is the condenser. Structural enhancements to be made in the components can prevent inefficiencies in the compressor. Also, the internal operating condition affected inefficiencies of components other than the evaporator and condenser. Both the design of the condenser and the evaporator and the interactions of components have had a notable impact on inefficiencies.

Ganjehsarabi et al. performed an exergoeconomic analysis of a heat pump tumble dryer using a cost estimating process [74]. Cotton fabric was dried in the experiments. The effects of drying temperature and the mass flowrate of the air on the system performance and the costs of the components were investigated parametrically. Fig. 12a schematically shows the experimental setup. As shown in Fig. 12b, the exergy destruction cost was highest in the condenser. The authors stated that the high cost of exergy destruction in this component is related to the high fuel cost. Gungor et al., for the first time in literature, conducted an advanced exergoeconomic analysis to assess the performance of each component of a gas engine-driven HPD system used for food drying [75]. This study showed that the investment cost was mainly affected by the internal inefficiencies, the structure, and the process of the system, while the interaction between the components does not importantly affect it. When the total avoidable cost is examined, it has been revealed that the drying channel, expansion valve, and condenser are the most critical components. Interior design changes played an important role in identifying the cost of each component.

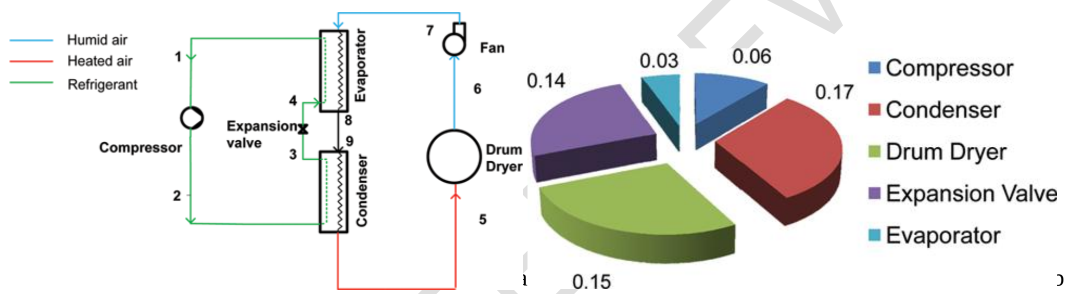

Fig. 12. (a) Schematic drawn of the experimental setup, (b) exergy destruction cost rate in system components [74]

Erbay and Hepbasli, for the first time in the literature, discussed the exergoeconomic performance of the ground source heat pump dryer (GSHPD) by using the specific exergy cost procedure [76]. The authors investigated the effect of dead state temperature change on the exergoeconomic performance of GSHPD and compared them with literature results. Variation of the dead state temperature affected heat exchangers. In parallel with the upward movement in the dead state temperature, the total exergy cost in the evaporator raised. Still, the exergoeconomic factor decreased due to the increase in the total cost. Aktaş et al. have developed an infrared-assisted heat pump dryer (IRAHPD) that merges all the superiorities of different drying techniques [77]. In this study, the authors aimed to investigate the drying kinetics of grated carrot, detect the dryer's exergy performance and compare the experimental outcomes of IRAHPD and HPD. The authors shared the results of the variation of drying time and energy consumption in Fig. 13a and exergy loss according to the moisture content in Fig. 13b according to different operating modes. As expected, IRAHPD is the most advantageous in terms of drying time, but the energy consumption is higher. The change in exergy loss values of all drying modes was almost parallel. Especially in the last drying stage, exergy losses increased and then decreased drastically.

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, for the first time in the literature, implemented conventional and advanced exergoeconomic analysis comparison to a GSHPD to detect possible improvement in system components [79]. Cost performance and thermodynamic inefficiencies of system components are analyzed in parts. The avoidable investment cost is considerably lower than the avoidable destruction cost. The most crucial system components for 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.

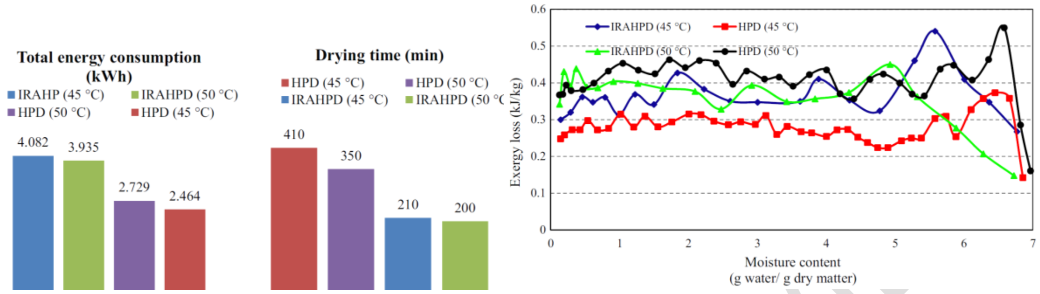

Fig. 13. In the different working mode (a) drying time and energy consumption comparison (b) change in exergy loss with moisture content [77]

Singh et al. developed a 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, manufactured convective type closed-loop SAHPD to conduct experimental research for basic HPD and SAHPD modes [81]. Thermodynamic, economic, and exergoeconomic performance parameters were compared for each drying mode. Compared to SAHPD, HPD has a lower drying temperature and drying time. Therefore, the energy, exergy, and exergoeconomic performance parameters of SAHPD were better. 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%

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[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	The drying system's conventional and advanced exergy efficiencies are 77.05% and 93.5%, respectively.
[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

This review focuses on studies that have contributed to the literature on heat pump dryers in recent years. This study presented studies on air, ground, and water source heat pump dryers, chemical heat pump dryers, domestic and commercial scale heat pump tumble dryers, solar or/and infrared assisted heat pump dryers, and heat pump dryers with integrated heat storage and heat recovery units to researchers working in this field. In the studies examined, the performance of the heat pump dryer was either investigated or compared with the performance of a different drying system. Moreover, this review also includes studies applying exergy analysis to heat pump dryers. In the studies examined, the authors evaluated the performance of heat pump dryers on drying time, COP, SEC, TEC, MER, SMER, exergy efficiency, exergy destruction, exergoeconomic factor, and many criteria.

In some studies, the authors compared the performance of heat pump dryers for drying different food. However, few studies have determined the quality characteristics of food products dried in a heat pump dryer. Some studies have revealed the drying characteristics and curves of food, and the compatibility of the obtained results with thin layer drying models has been investigated. Particularly, studies comparing air and nitrogen as drying mediums

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have attracted attention. Namely, the performance of heat pump dryers in these drying environments is essential. In addition, the drying characteristics of all food products desired to be dried in these alternative drying mediums will be re-determined, and new standards will emerge.

The authors have implemented applications such as changing the mixing ratio of return air with fresh air, heat storage units, heat recovery units, and unit rooms, especially to improve the performance of heat pump dryers. The results obtained from these applications have been positive. This situation is a sign that heat pump dryers can be developed further. Also, solar and/or infrared-assisted heat pump dryers were more efficient than simple heat pump dryers.

Exergy analysis, which is also used as a performance evaluation method in all applications in the energy field, has shown effective results in heat pump dryers. In particular, advanced exergy analysis has been quite functional in identifying the components that need improvement. Exergoeconomic analysis, which combines exergy and economic evaluation, was used to determine the exergy destruction costs. Thus, a direct contribution was made to the make-decision process. Beyond that, some studies have offered the possibility of making effective cost improvement strategies for system components with advanced exergoeconomic analysis.

As a result, evaluated studies have accepted the advantage of heat pump dryers having low operating costs, efficiently drying, keeping the drying conditions under control, and being environmentally friendly. However, the high initial investment cost is still expressed as the most significant disadvantage. The most common HPD on the market is heat pump tumble dryers used to dry clothes. Heat pump dryers for drying food are less common on the market. In the drying sector, heat pump dryers have been more hesitant. More research on these dryers is needed to overcome this situation. In particular, studies where researchers from different disciplines come together, can be carried out. Of course, it is crucial for the engineers working in this field to contribute as much as the academicians. Especially in air source heat pump drying applications, the heat source may be insufficient in different meteorological conditions. In the future, this problem will turn into a subject of study. Adaption of heat recovery, heat storage, and phase change materials applications to heat pump dryers can be investigated. The environmental impact method should be added to the energy, economy, and exergy analyses used to measure the performance of HPD. Studies should be carried out on automation and artificial intelligence applications that will prevent manual use of HPD. Studies on inert gases as an alternative to air as a drying medium may be a popular research topic in the future.

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