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REVIEW

Comprehensive assessment of heat pump dryers for drying agricultural products

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Abstract

Fruits and vegetables are agricultural products that require preservation to enhance and protect shelf life, encapsulate natural flavour, and retain nutritional content. Globally, agricultural products are preserved by a range of means, the most prevalent of which is the heat pump dryer, which produces the best results even in unfavourable climatic conditions. Heat pump dryers come in different types and their performance varies depending on the type. This study aims to evaluate recently developed heat pump dryers based on key performance indicators, impacts on food colour and nutritional content, techno-economic, exergoeconomic, and environmental issues associated with the development of heat pump dryers, which are underrepresented in most of the existing heat pump dryers' reviews. This study also discusses mathematical drying kinetic models, and regulation or policy aspects related to the development of heat pump dryers. In the present study, the results on performance analysis indicate that heat pump dryers examined were effective in reducing drying time and obtaining high coefficients of performance ranging from 1.94 to 5.338 and specific moisture extraction rate ranging from 0.156 to 9.25 kg/kWh, as well as significantly reducing energy consumption by up to 80%. The nutritional composition and colour results show that heat pump dryers maintain the maximum nutrient content while also improving colour. The expansion valve has the lowest exergoeconomic factor of all heat pump dryer components, whereas the compressor has the highest cost of exergy destruction in general, according to the results of exergoeconomic analysis. Techno-economic analysis results demonstrated that most developed heat pump dryers have short payback periods ranging from 1.6 to 3.6 years. However, due to a lack of research in this field, the environmental implications of heat pump dryers are unknown. As per the findings of this study, future research in this field should focus on the design of simple and low-energy heat pump dryers, life cycle, techno-economic, and exergoeconomic assessments.

KEYWORDS
biomaterials, economic, efficiency, heat pump dryers, life cycle analysis, nutritional content

1 | INTRODUCTION

The preservation of therapeutic plants, vegetables, and fruits requires the application of adequate methods to guarantee not only the best preservation but also protect the nutritional content, flavour, and texture of the dried product. Moreover, to prevent the development of microorganisms such as bacteria and fungi which can lead to food intoxication.[1] The choice of conservation method is thus essential, whether in a domestic or industrial environment. Drying, salting, freezing, irradiation, packaging and fermentation are some of the methods used to preserve food.[2] Drying has significant advantages over other preservation methods since the energy required for drying can be obtained from a variety of renewable or nonrenewable sources.[3] This method of food preservation involves removing some or all of the food's water content. Microorganisms would be unable to multiply, and most chemical and enzymatic activities are slowed as a result of the decrease in water activity. With drying, a good part of vitamins, minerals, and flavours are preserved. Drying also reduces the risk of food intoxication but also reduces the weight and volume of food because dried products occupy much less space than fresh products hence easy storage, packaging and transportation.[4]

Although drying methods currently attract many researchers, it should be noted that this technique is not new. It has been used since ancient times. This is why this technique has continued to develop, and there are many drying methods to date like solar drying, fluidized bed drying, freeze-drying, spouted bed drying, air drying and vacuum drying.[4–9] These methods abound from all four corners of the globe, delighting thousands of consumers and professionals who view this abundance as a means of selecting the best drying process for their commodities. Moreover, the ideal drying method, concerning efficiency and energy usage, is the use of solar dryers. It works simply thanks to the sun and allows a slow and gentle drying of food. As a result, a variety of solar dryers have been produced all over the world. These different varieties can be first categorized by the type of drying chamber, which can be a cabinet, a greenhouse, or a tent. Second by the type of airflow, which might be passive or active. Finally, depending on how heat is transferred from the sun to the product (direct, indirect, hybrid, or mixte).[10]

Unfortunately, solar dryers have some drawbacks such as food degradation due to direct exposure to sunlight; loss of vitamin B and C; and the long drying time, all these result into a product of poor quality.[10–14] To address this issue, heat pump dryers were developed as a solution to dry foodstuffs or biologically active products, hence resolving the issues encountered with solar dryers. Heat pump dryers are continuously being developed all around the world, and their effectiveness has been shown to outperform conventional drying processes.[15–20] Heat pump dryers are characterized by their energy efficiency of up to 91.95%, low power consumption which ranges between 60% and 80%, low cost, good drying efficiency of up to 95%, high coefficient of performance of up to 5, low drying temperature of up to 80%, short drying time, low relative humidity which varies from 10% to 80% and thus the ability of nutrient retention of the dried products.[21–27]

The ability to control the temperature of the drying air and humidity while recovering energy from exhaust are the primary advantages of heat pump dryers. Numerous studies have shown the importance of heat pump dryers for drying different heat sensitive products for example therapeutic plants, vegetables and fruits.[28–31] The purpose of this study is therefore to qualitatively and quantitatively review the various types of heat pump dryers that have recently been developed. The first part deals with the operation of these various heat pump dryers from the key performance indicators that define the drying kinetics and the energy analysis. In this part, policy and regulatory issues pertaining to the development of heat pump dryers are also discussed. Second, to substantiate the efficiency of heat pump dryers and motivate further research aimed at enhancing efficiency, this study also highlights the impacts of heat pump dryers on food colour and nutritional content. Finally, this study addresses the techno-economic, exergoeconomic and environmental challenges associated with the development of heat pump dryers, which are underrepresented in heat pump dryers' review. At the end of the paper, research gaps that result from our findings are highlighted and could benefit from further research.

2 | PERFORMANCE ANALYSIS

Numerous studies have shown the effectiveness of heat pump systems used for drying and the significance of selecting drying as the best method for food preservation.[32–35] The use of heat pumps for drying spreads all over the world and to this day heat pumps occupy a preponderant place in research concerning the drying of biomaterials, that is why many heat pump dryer technologies keep emerging.[6,36] Heat pump dryer technologies help to handle problems that the population encounters when it comes to meeting their drying demands for fruits, vegetables, and medicinal plants. A heat pump dryer's performance varies depending on the technology and, in some cases, climatic conditions perspective. Several parameters can be studied to analyse the performance of these various heat pump dryer technologies. All these parameters can be grouped into two groups. On the one hand, we have the kinetic parameters of drying whose major parameters are the drying time, the velocity and the moisture content.[37] On the other hand, we have the energy parameters which group together the major parameters such as the coefficient of performance and the specific moisture extraction rate.[38] The most recent heat pump dryer studies focused on three types of heat pump dryers, namely hybrid heat pump dryers, ground source heat pump dryers and air source heat pump dryers.

2.1 | Hybrid heat pump dryer

The utilization of heat pumps in conjunction with solar energy has been the focus of recent research on hybrid heat pump dryers in the drying process. As a result, solar-assisted heat pump dryer technologies and solar-infrared heat pump dryer technologies have received a lot of attention. But other technologies are not left out since the combination of the heat pump with photovoltaic, coulomb force, radiofrequency, ultrasound and waste heat recovery has shown good results, according to numerous studies. This section explores the various types of heat pump dryers stated above and illustrated in Figure 1.

2.1.1 | Solar-assisted heat pump dryer

Day by day, interest in solar-assisted heat pump dryers continues to grow, as numerous studies have been able to show the effectiveness of this type of dryer all over the world for drying biomaterials. Solar-assisted heat pump dryers have been found to be effective in reducing energy consumption and drying time. Xu et al.[39] have proposed a solar-assisted heat pump dryer incorporating five modes for drying mushrooms. This heat pump dryer system's simple design allows it to transition from one drying mode to another at any moment, depending on the environmental conditions. All five drying modes performed well, according to the results. Furthermore, the energy savings rate could reach 37.96%.

Solar-assisted heat pump drying was also employed for drying pumpkins by Dai et al.[40] Compared with a typical heat pump dryer, this dryer showed good results in reducing drying time by 40% and energy consumption. Hu et al.[41] developed a solar-assisted heat pump dryer to dry wolfberry. The power consumption was found to be less than that of a heat pump dryer alone, and during the summer drying procedure, the power consumption was reduced by 9.1 kWh in comparison to the autumn drying. A solar drying system with a direct expansion heat pump was conceived and built by Hao et al.[15] to tackle the difficulties of instability and low controllability associated with solely employing solar energy in drying. The authors used lemon as drying material. The results revealed that the moisture content curve appeared to be constant after 7 h of drying. However, the specific moisture extraction ratio for the system was 0.85 kg/kWh. In addition, the solar radiation intensity had an important impact on the coefficient of performance and the drying chamber's temperature. To dry misai kucing leaves, Gan et al.,[42] used a solar-assisted heat pump drying system. The system exhibited a shorter drying time with a difference of 4 h compared to the traditional solar dryer. However, solar-assisted heat pump dryers also work well when integrated with a storage system or thermal recovery unit. In Ismaeel and Yumrutas,[43] the authors examined the efficiency of a solar heat pump drying system with heat recovery system and an underground storage system. Annual energy saving was determined to be 21% when compared to nonheat recovery systems. Finally, to dry mangoes, Wang et al.[44]

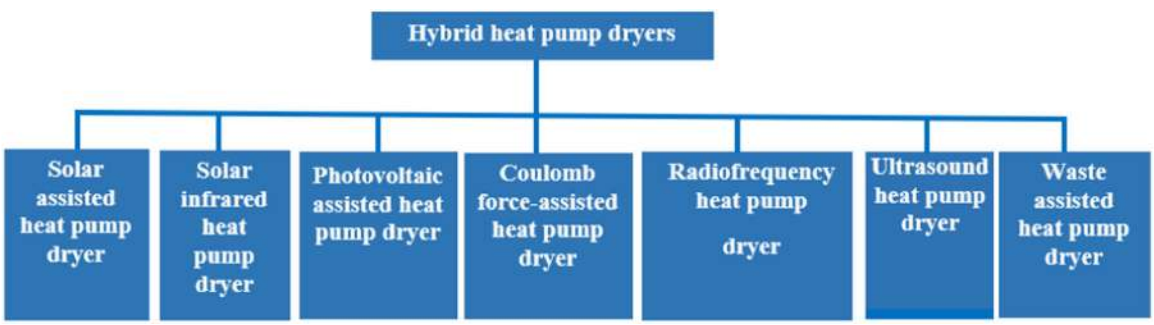

FIGURE 1 Various types of hybrid heat pump dryers

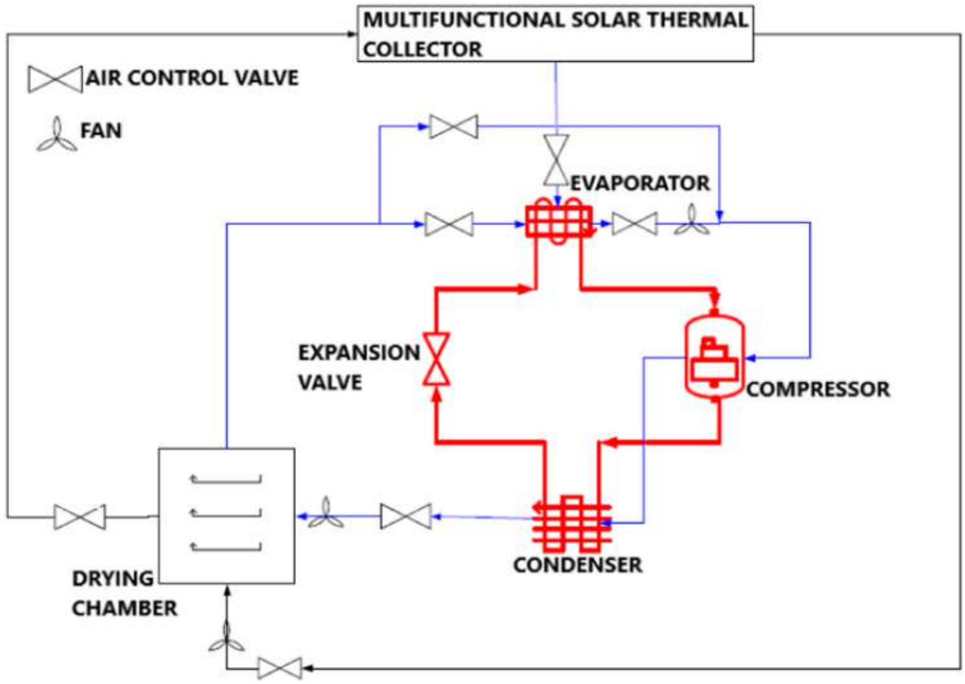

FIGURE 2 Schematic diagram of solar-assisted heat pump dryer[46]

investigated a solar-assisted heat pump dryer with secondary heat recovery. Solar mode was found to be more efficient than the heat pump mode, saving 3.5 kWh in power consumption. In general, solar-assisted heat pump dryers provide good performance; Singh et al.[45] research has also demonstrated this by obtaining higher energy and drying efficiency. Figure 2 shows a schematic diagram of a solar-assisted heat pump dryer.

2.1.2 | Solar-infrared assisted heat pump dryer

The solar-infrared assisted heat pump dryer has gotten very little attention. To dry banana chips, Singh et al.[47] fabricated and tested a solar infrared-assisted heat pump dryer consisting of an infrared heating system, a drying system, a heat pump system, a solar heating system and a medium drying cycle. Solar-infrared-assisted heat pump drying, solar-assisted heat pump drying, infrared-assisted heat pump drying and simple heat pump drying were used to compare the system in four different operational modes. The best average moisture extraction rate was produced by the solar-infrared-assisted heat pump dryer, while the worst was achieved by the conventional heat pump dryer. The highest specific moisture extraction rate was achieved with solar-assisted heat pump drying, whereas the lowest was achieved with infrared-assisted heat pump drying. Ha et al.[48] investigate the use of an infrared-assisted heat pump dryer to dry lime slices. Experiments were carried out with a 1.2 kg/batch drying capacity and a 1.2 m/s drying air velocity. The results revealed that a good effective drying range was reached utilizing 3 mm thick lime slices, a drying chamber temperature of 42.5 or 45°C, and a radiation intensity of 110 to 300 W/m^2. Xiaoyong et al.[49] stated that heat pump drying coupled with far-infrared radiation could be used to efficiently dry yam chips. Results showed that with the increased power supplied to the far-infrared radiation heaters, energy consumption was greatly reduced. The work carried out by Aktaş et al.[50] demonstrated that drying food using a heat pump and an infrared heater to dry food is a successful and efficient method.

Figure 3 illustrates the solar-infrared heat pump dryer.

2.1.3 | Photovoltaic-assisted heat pump dryer

Despite the few studies on photovoltaics integrated with heat pump dryers, the work carried out by Kosan et al.[51] has made it possible to understand that the combination of photovoltaic system and heat pump dryer can give better results and achieve performance equal to other drying systems. The experimental device of this type of dryer usually includes a drying chamber, a photovoltaic system and a heat pump.[51] The photovoltaic-assisted heat pump dryer also operates better than other heat pump dryers and

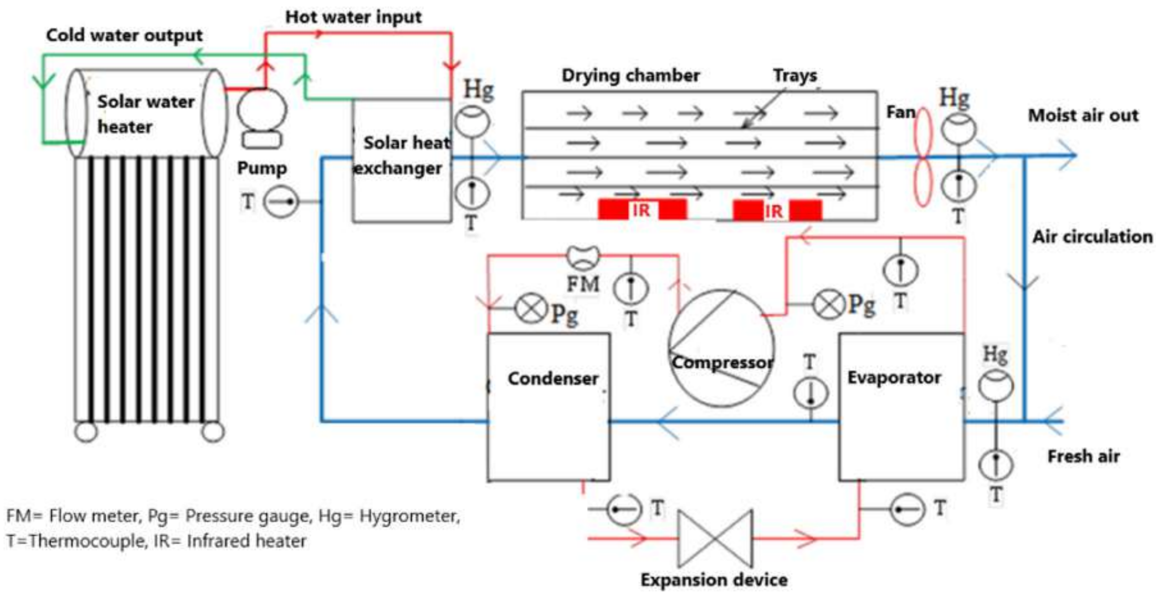

FIGURE 3 Schematic diagram of the solar-infrared heat pump dryer[47]

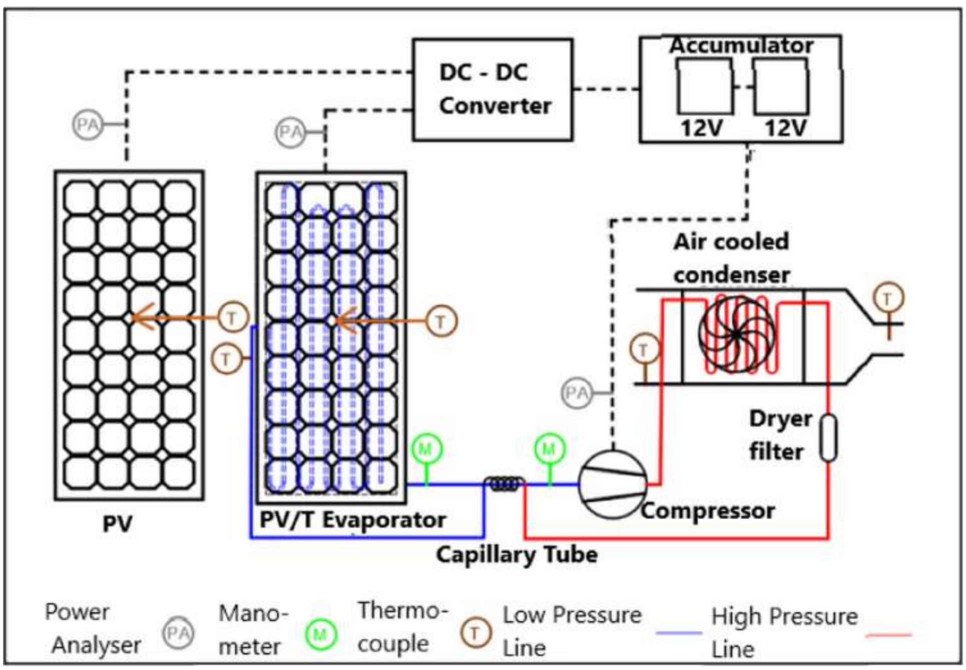

FIGURE 4 Symbolic diagram of the photovoltaic/thermal assisted heat pump dryer[51]

gives good results. This is exemplified by the photovoltaic-assisted heat pump dryer developed by Candan et al.,[52] to dry agricultural products such as bananas. With this device, it was possible to have a specific humidity extraction rate of an average value of 0.45 kg/kWh, which makes it possible to classify this system among the most efficient hybrid heat pump dryers. Houhou et al.[53] developed a novel form of solar heat pump dryer that was powered entirely by photovoltaic panels based on a simulation. A mathematical model describing the entire drying process was developed in able to design this system. The results of simulations at various temperatures revealed that, in comparison to velocity, a crucial parameter was the temperature of the drying air; because the product moisture content decreased from 0.75 to 0.3 kg/kg (kg water/kg dry product), when the drying temperature raised from 45°C to 55°C. Figure 4 shows the symbolic diagram of the photovoltaic/thermal-assisted heat pump dryer.

2.1.4 | Coulomb force-assisted heat pump dryer

The main components of this system are a high-voltage wire mesh and a heat pump dryer. The Coulomb force is created when the product is held near a high-voltage and low-frequency mesh. The resulting force increases moisture diffusion in the product, which is then dried by the heat pump dryer's airflow. To dry lemons, Lee et al.[54] developed a coulomb force-assisted heat pump dryer. When compared to drying lemon slices using merely a heat pump dryer, the effective moisture diffusivity and the drying rate increased by 26%. Lee et al.[55] dried lemon in an oven and a coulomb force-assisted heat pump dryer to evaluate their performance. Oven drying at various temperatures exhibited a high drying rate as the drying temperature increased. Figure 5 shows the schematic diagram of the coulomb force-assisted heat pump dryer.

2.1.5 | Radio frequency heat pump dryer

Food and agricultural products can be dried using a radio frequency heat pump dryer.[56–60] Radio frequency drying is attractive because of its deep penetration, rapid and volumetric heating and moisture self-balancing properties. The combination of radio frequency drying and heat pump drying uses both traditional drying technologies and radio frequency heating to optimize energy efficiency and product quality. Recent studies are rare despite the efficiency of this type of heat pump dryer. Radio frequency technology combined with a heat pump dryer for drying Ganoderma lucidum was fabricated by Hay et al.[61] Increases in radio frequency power and drying air temperature considerably enhanced the drying rate, according to the findings. Furthermore, the drying rate remained unchanged by the drying air velocity and increasing radio frequency power reduced the drying time. Kien et al.[62] investigated a radiofrequency-assisted heat pump dryer to dry Ganoderma lucidum. According to the findings, as the radio frequency power increased and drying air temperature, the drying rate increased, but as the drying air velocity rose, the drying rate decreased. The schematic diagram of the radio frequency heat pump dryer is shown in Figure 6.

2.1.6 | Ultrasound-assisted heat pump dryer

The ultrasound-assisted heat pump dryer is a promising method for drying. Yang et al.[63] explored the feasibility of ultrasound-assisted heat pump intermittent drying to avoid seed quality degradation and high energy consumption caused by the long-time ultrasound application. The findings revealed that even though the introduction of intermittent drying was important for reducing energy usage, its impact on seed germination was not as positive as projected. Additionally, the response surface methodology also determined that the optimal drying parameters were, 102.80 W ultrasound power, 37.10°C and 0.59 intermittency ratio. Yang,

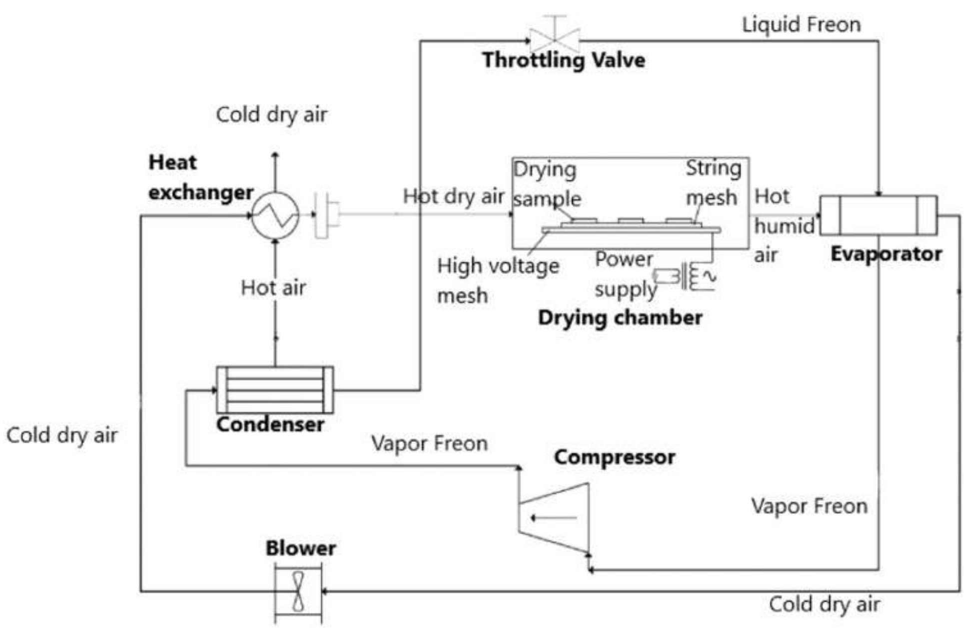

FIGURE 5 Schematic diagram of the coulomb force-assisted heat pump dryer[54]

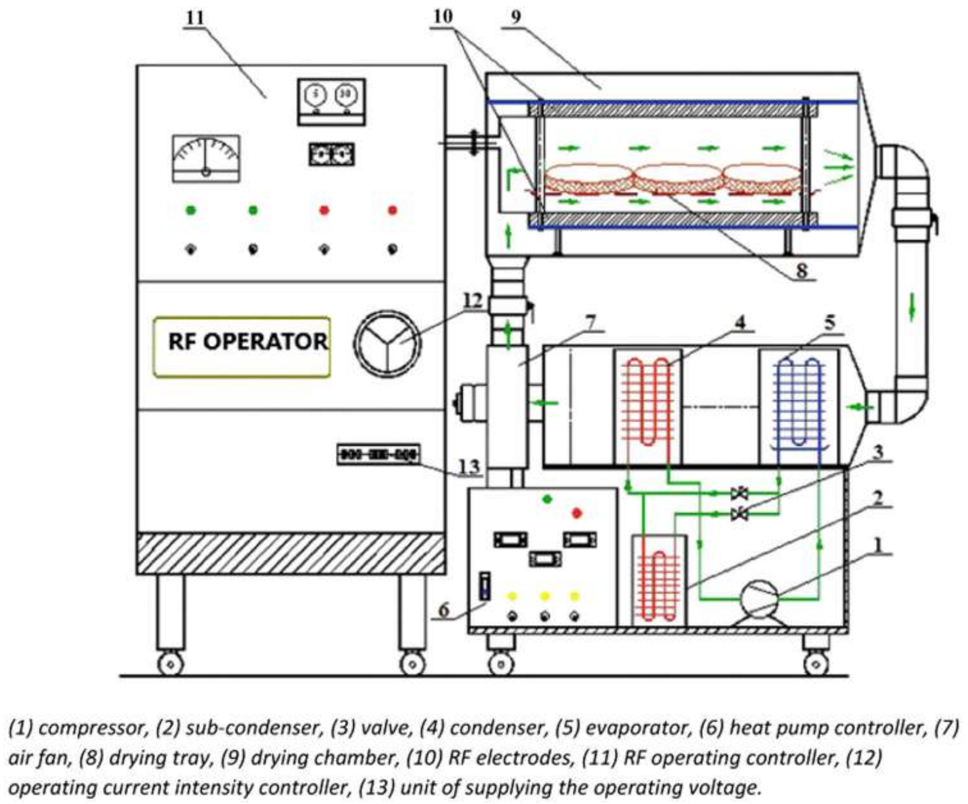

FIGURE 6 Schematic diagram of the radio frequency heat pump dryer.[61] RF-assisted heat pump dryer model

et al.[64] determined the influence of drying temperature and ultrasonic factors on pea seed drying kinetics. The results revealed that high temperature and ultrasound treatment enhanced pea seed drying kinetics in a substantial way, reducing drying time and increasing diffusion coefficient. Kiwifruit slices were subjected to contact ultrasound-assisted heat pump drying experiments by Liu et al.[65] The findings revealed that this technology significantly increased the rate of dehydration and reduced drying time. The hardness and brittleness of dried kiwi fruit samples could be reduced by using ultrasound in a heat pump dryer. Figure 7 shows the ultrasound-assisted heat pump dryer.

2.1.7 | Waste heat-assisted heat pump dryer

Although there is not enough research to support the effectiveness of this new type of dryer, using waste heat recovery from various primary engines to assist heat pump dryers is an interesting alternative for the drying of biomaterials. The research carried out by Singh et al.[66] has given some insight into this novel heat pump dryer design by developing a waste-assisted heat pump dryer using the waste heat recovery from diesel engine exhaust, for drying radish chips. Several performance parameters have been examined to compare this technology with the heat pump dryer alone. The drying time was the shortest for the waste-assisted heat pump dryer, which reduced the moisture content of radish chips from 93.5% to 10.5%. When compared to a waste-assisted heat pump dryer, the heat pump dryer alone had a higher coefficient of performance, while the waste-assisted heat pump dryer had a higher specific moisture extraction rate. Figure 8 shows a photograph of the waste-assisted heat pump dryer.

2.2 | Ground source heat pump dryer

Although this technology is among the most efficient types of heat pump dryers, ground source heat pump dryers have attracted the interest of a few researchers in food drying applications. Wu et al.[67] designed a ground source heat pump dryer for theoretical analysis. The comparison was made to the closed air source heat pump. The numerical calculations for the drying system were done in MATLAB. Results revealed that the coefficient of performance ranged from 3.2 to 5.2 when the drying temperature was between 40°C and 60°C. In addition, the highest and

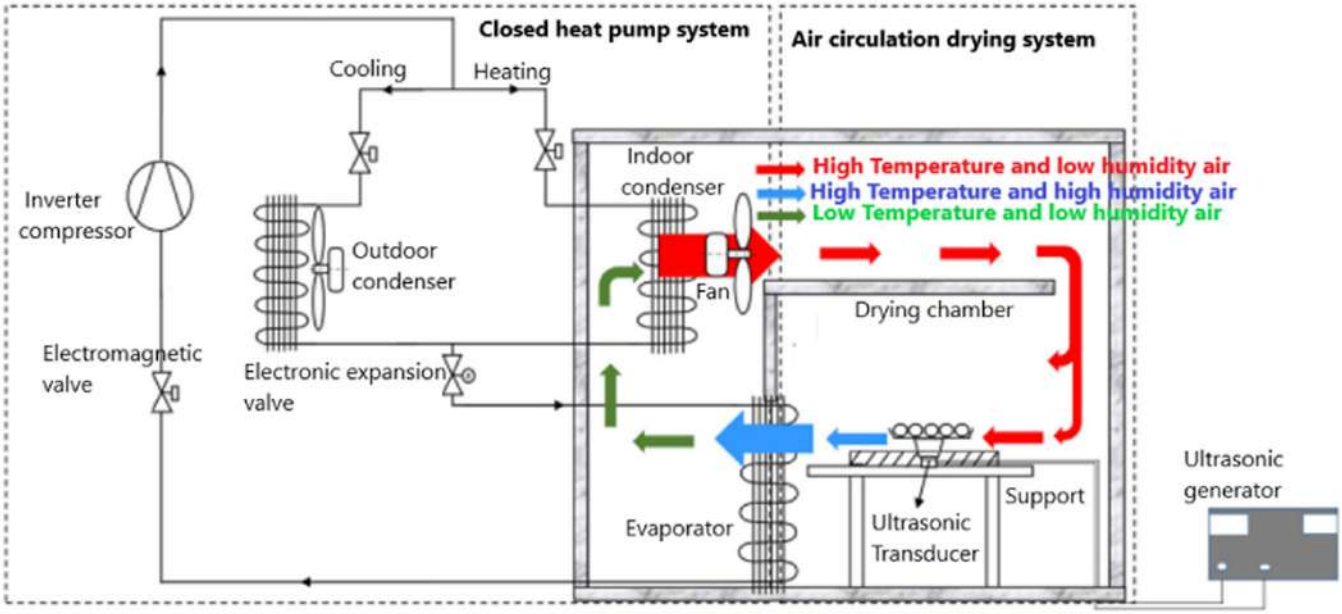

FIGURE 7 Schematic diagram of the ultrasound-assisted heat pump dryer[63]

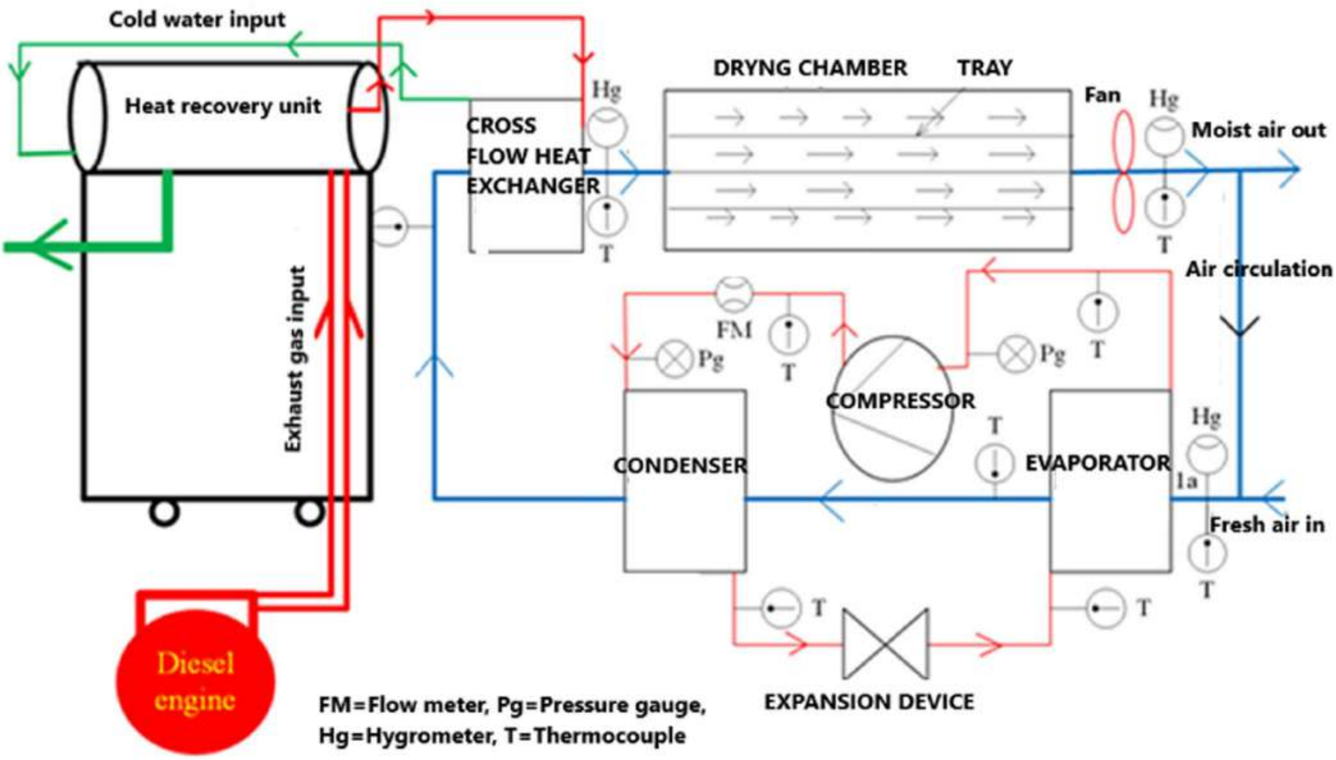

FIGURE 8 Representation of diesel engine exhaust heat recovery-assisted heat pump dryer[66]

lowest specific moisture extraction rates for ambient temperatures of 20°C were 4.4 and 1.4, respectively, and the highest and lowest specific moisture extraction rates for ambient temperatures of −10°C were 2.6 and 1.1, respectively. Furthermore, due to a higher specific moisture extraction rate, the ground source heat pump drying system outperformed the closed air source heat pump drying system. Figure 9 shows a schematic diagram of the ground source heat pump dryer.

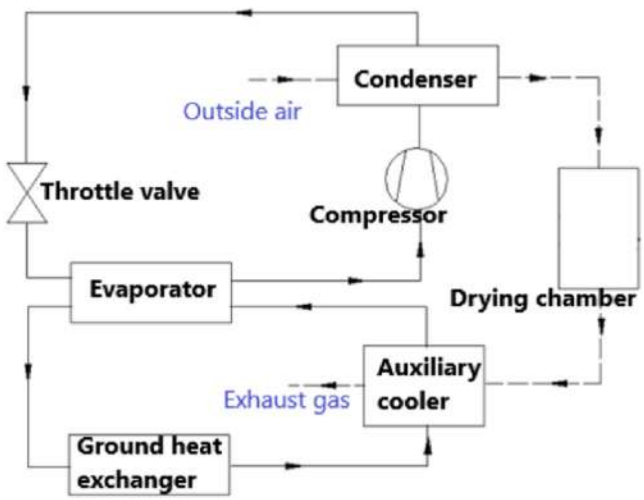

FIGURE 9 Schematic diagram of the ground source heat pump dryer[67]

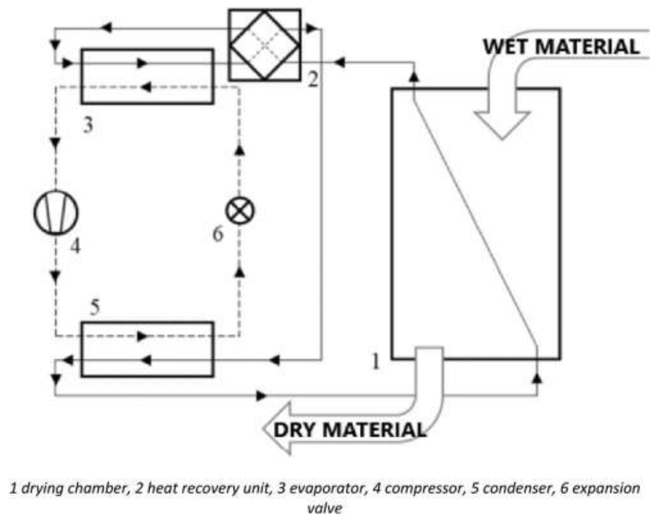

FIGURE 10 Schematic diagram of the air source heat pump dryer[32]

2.3 | Air source heat pump dryer

Compared to many drying methods, air heat pump dryer is preferable because this system is more energy and cost-saving.[32] Several new designs of air source heat pump dryers have recently been featured in various publications. All of these innovative designs of air source heat pump dryers improve the effectiveness of this type of dryer for drying biomaterials, and this system produces good results regardless of the dried product. To dry garlic slices, Liu et al.[68] proposed an air heat pump dryer. According to findings, in summer, the humidity and high temperature of the ambient air lowered the moisture extraction rate and increased the specific moisture extraction rate for open-type heat pump dryers. The low temperature and humidity of the ambient air, on the other hand, enhanced the moisture extraction rate while decreasing the specific moisture extraction rate throughout the winter. When the bypass air rate reached 0.4, the specific moisture extraction rate of the closed-type heat pump drier was at its maximum. As the bypass air rate increased, the moisture extraction rate decreased.

Shen et al.[69] proposed an air heat pump combining single and cascade cycle modes for drying. According to the results of this study, the coefficient of performance of single mode was higher. Liu et al.[70] proposed an existed enclosed fixed-frequency air source heat pump drying system. The drying performance of this system was analysed. System performance was improved by adjusting airflow ratios via an air bypass duct, according to the findings. A batch-type convective small heat pump dryer was manufactured by Singh et al.[71] The experiment involved drying various agricultural products. Based on the recirculation of dryer exhaust air within the system, the system worked in two modes: open and closed systems. According to the findings, in the open and closed systems, the total energy consumption for banana chips was 3.3 and 2.41 kWh, and for potato chips, it was 3.564 and 3.51 kWh. The closed system had a greater specific moisture extraction rate, whereas the open system had a better coefficient of performance. In addition, for both the drying of bananas and potato chips, total exergy destruction was highest for the closed system. The schematic diagram of the air source heat pump dryer is shown in Figure 10.

3 | SUMMARY OF PERFORMANCES ANALYSES

Table 1 highlights the most studied performance parameters for drying kinetic analysis and energy analysis of different types of heat pump dryers that have been presented above. Admittedly, the heat pump arouses the interest of many researchers around the world, but recent research in this field is concentrated in China, where we feel a constant involvement, because all the types of heat pumps existing today have already been the subject of a study in this country. However, concerning all the parameters studied, it is noted that the moisture content, the drying time, the specific moisture extraction rate and the coefficient of performance are among the most studied parameters. According to most of the results examined, air temperature and mass are inversely correlated with coefficient of performance, but air velocity is positively correlated.

However, increasing air velocity and temperature, reduces drying time, while increasing mass extends drying time. The specific moisture extraction rate, on the other hand, decreases when the air temperature increases, but

TABLE 1 Performance analysis results

Authors	Drying system	Country	Drying temperature (°C)	Final moisture content	Initial weight (kg)	Product dried	Thickness (mm)	Velocity (m/s)	SMER (kg/kWh)	COP	Drying time
	Hybrid source heat pump dryer										
[39]	SAHPD in different modes:										
	ISDS mode	China	50	50%	3	Mushroom	NA	NA	3.56	NA	6 h
	ICHPDS mode	China	60, 55 and 50	NA	1.5, 2 and 2.5	Mushroom	NA	1.5, 2.5 and 3.5	**a)** 0.163, 0.184 and 0.168 respectively at 1.5, 2.5 and 3.5 m/s. **b)** 0.156, 0.168 and 0.158 respectively at 1.5, 2 and 2.5 kg **c)** 0.184, 0.178 and 0.184 respectively at 50, 55°C and 60°C	**a)** 2.11, 2.96 and 3.35 respectively at 1.5, 2.5 and 3.5 m/s. **b)** 3.35, 3.35 and 2.86, respectively at 1.5, 2 and 2.5 kg **c)** 2.96, 2.51 and 2.43 respectively at 50, 55°C and 60°C	**a)** 20, 17 and 17 h respectively at 1.5, 2.5 and 3.5 m/s. **b)** 15, 17 and 19 h respectively at 1.5, 2 and 2.5 kg. **c)** 13, 15 and 17 h respectively at 60, 55°C and 50°C
	SAHPD in open mode	China	59.17	NA	2	Mushroom	NA	3.5	0.225	3.08	12 h
	SAHPD in closed mode	China	62.38	NA	2	Mushroom	NA	3.5	0.27	2.68	9 h
	SAHPD in semi-open mode	China	60.83	NA	2	Mushroom	NA	3.5	0.23	3.20	12 h
[41]	SAHPD	China	40 to 70	12%	50	Wolfberry	NA	1	NA	NA	59 h at 40°C and 8 h at 70°C

TABLE 1 (Continued)

Authors	Drying system	Country	Drying temperature (°C)	Final moisture content	Initial weight (kg)	Product dried	Thickness (mm)	Velocity (m/s)	SMER (kg/kWh)	COP	Drying time
[15]	SAHPD	China	51.8 (maximum)	0.54 (g water/g dry)	0.4	Lemon	3	NA	0.856	3.63 (maximum)	7 h
[42]	SAHPD	Malaysia	33.1	10%-12%	0.01	Misai kucing leaves	NA	6.5	NA	NA	39.8 h
[40]	SAHPD	China	67.40	0.95 ± 0.05 (g/g dry basis)	NA	Pumpkin slice	4	NA	0.95	NA	7 h 34 min
[43]	SAHPD with storage and HRU	Turkey	60	10%	NA	Wheat	NA	NA	9.25	5.28	NA
[44]	SAHPD with HRU in two modes:										
	HPD	China	45	0.25 dry basis	80	Mango	NA	NA	1.82	3.48	14 h
	SAHPD	China	45	0.25 dry basis	80	Mango	NA	NA	2.05	3.69	16.3 h
[47]	SIAHPD in different modes:										
	SIAHPD	India	65.7	11.5%	NA	Banana chips	2	0.8	1.351	1.94	180 min
	SAHPD	India	65.7	11.5%	NA	Banana chips	2	0.8	1.45	2.04	225 min
	IAHPD	India	50.54	11.5%	NA	Banana chips	2	0.8	0.968	2.303	225 min
	HPD	India	50.25	11.5%	NA	Banana chips	2	0.8	0.975	2.618	345 min
[48]	SIAHPD	Viet Nam	42.5–45	13%	1.2	lime slices	3	1.2	NA	NA	10 h
[50]	SIAHPD	Turkey	45	0.14 g water/g dry basis	1	Carrot	1.5	0.5	NA	4.39	410 min

(Continues)

TABLE 1 (Continued)

Authors	Drying system	Country	Drying temperature (°C)	Final moisture content	Initial weight (kg)	Product dried	Thickness (mm)	Velocity (m/s)	SMER (kg/kWh)	COP	Drying time
[52]	PVAHPD	Turkey	31.27	NA	2.5	Banana chips	4	2.77	0.45	5.338	50 min
[53]	PVAHPD	China	45–55	0.3 Kg/Kg	10	NA	NA	1-3	NA	NA	NA
[54]	CFAHPD	Malaysia	21-23	NA	NA	Lemon slices	2.5-3.5	1 − 1.2	NA	NA	101.40 h ± 1.97
[61]	RFAHPD	Vietnam	45	13% Wet basis	20	Ganoderma lucidum	15	1.2	NA	NA	400–600 min
[62]	RFAHPD	Viet Nam	47	NA	NA	Ganoderma lucidum	NA	1.53	NA	NA	409 min
[63]	UAHPD	China	105 ± 1	14.5 g/g dry basis	0.07	Adzuki bean seeds	6.40 ± 0.15	0.7	NA	NA	24 h
[64]	UAHPD	China	40	0.0532 dry basis	0.09	Pea seed	NA	0.7	NA	NA	12 h
[65]	UAHPD	China	30 and 40	0.2-0.3 g/g dry basis	0.08	Kiwifruit	5	1	NA	NA	450 min at 30°C and 390 min at 40°C
[66]	WHR-HPD	India	65–70°C	10.5%	5	Radish	2	0.5 to 2.5	1.39, 1.6436, 2.158, and 2.4 kg/kWh, respectively for the open-loop simple-HPD, closed-loop simple-HPD, open-loop WHR-HPD, and closed-loop WHR- HPD.	5.34, 4.25, 5.18, and 3.48 respectively for the open-loop simple-HPD, closed-loop simple-HPD, open-loop WHR-HPD, and closed-loop WHR-HPD.	135 min

TABLE 1 (Continued)

Authors	Drying system	Country	Drying temperature (°C)	Final moisture content	Initial weight (kg)	Product dried	Thickness (mm)	Velocity (m/s)	SMER (kg/kWh)	COP	Drying time
	Ground source heat pump dryer										
[67]	Open-circuit GSHPD	China	40–60	NA	NA	NA	NA	NA	4.4 (highest)	3.2-5.2	NA
	Air source heat pump dryer										
[68]	ASHPD	China	50	10% wet basis	15	Garlic slices	3	1	1.136 ± 0.001	NA	270–300 min
[69]	ASHPD	China	70	NA	NA	NA	NA	NA	NA	2.6 (Highest)	NA
[70]	ASHPD	China	30, 35 and 40	20%	0.5	Carrot	3	1	NA	NA	315 min at 30°C; 294 min at 35°C and 281 min at 40°C
[71]	ASHPD	India	50.5 and 50.4 respectively for drying banana and potato in the closed system.	11.6% and 11.5% for banana and potato.	4 kg of Banana and Potato	Banana and Potato	2	6	1.248 and 1.0498 respectively for drying banana and potato in the closed system.	3.09 and 2.85 respectively for drying banana and potato in the closed system.	220 and 320 min respectively for drying banana and potato in the closed system.
			41.4 and 40.8 respectively for drying banana and potato in the open system.						0.924 and 0.981 respectively for drying banana and potato in the open system.	3.89 and 3.93 respectively for drying banana and potato in the open system.	300 and 370 min respectively for drying banana and potato in the open system.

rises as the air velocity and mass increase. As the result, the greatest specific moisture extraction rate of 9.25 was obtained by the solar-assisted heat pump dryer integrated with heat recovery unit according to the results presented in Table 1. Overall, the analysis of all parameters presented in Table 1 reveal that all types of heat pump dryers give good results, especially in reducing the mass of dried products and the moisture content (up to 10%) in a short drying time compared to conventional dryers. The results of the table also showed that, the photovoltaic-assisted heat pump dryer has the highest coefficient of performance value of 5.338 followed by the solar-assisted heat pump dryer, which proves heat pump dryers' efficiency. Unfortunately, it is difficult to make a comparison between all these types of heat pump dryers presented in Table 1, because research has been carried out on different climatic conditions and specific agriculture products. Indeed, environmental conditions have a direct impact on heat pump dryers because the ambient temperature greatly influences the performance of heat pump dryers without forgetting the different types of seasons. Also, the coefficient of performance, the specific moisture extraction rate and the drying time vary with environmental conditions. Similarly, the type of agricultural products greatly affects the coefficient of performance, the specific moisture extraction rate and the drying time because the values of its parameters vary depending on whether the dried products have low or high moisture content. The data reported in Table 1 show that the type of heat pump dryers utilized also has a considerable influence on the coefficient of performance, the specific moisture extraction rate and the drying time. By analyzing the results of Table 1, the drying time decreases significantly depending on the mode of operation of the heat pump dryer used. Wang et al.,[44] demonstrated this by drying 80 kg of mango till the final moisture content was 0.25 dry basis using two different operation modes. The results revealed that the heat pump dryer mode gave a drying time of 14 h while the solar-assisted heat pump dryer gave a drying time of 16.3 h. Singh et al.[47] achieved similar results by drying banana chips to a final moisture content of 11.5% using five different drying modes. The banana chips dried in 180 min with the solar-infrared heat pump dryer and 225 min with the solar-assisted heat pump dryer.

4 | DRYING KINETICS MATHEMATICAL MODELS APPLIED IN HEAT PUMP DRYERS

Modelling the drying kinetics is one of the most important aspects to consider when manufacturing heat pump dryers since it allows for better design of all major components of the heat pump dryer to reach the desired final moisture content after drying. As a result, various drying models exist and are used to determine the drying kinetics of agricultural products. These models all use unique equations. In general, the modelling of these equations or models is influenced by a variety of parameters, including constant empirical coefficients. When the model fits the experimental data, it is considered satisfactory or effective. These models are evaluated or contrasted in general terms using statistical parameters such as coefficient of determination, root mean square error, and reduced χ^2. The best model for predicting the drying kinetic is then chosen, with the highest coefficient of determination, the lowest root mean square error, and the lowest χ^2.[72–74]

To date, the Newton, Logarithmic, Page, Two-term, Wang and Singh, Approximation of diffusion, Modified Henderson and Pabis Midilli–Kucuk model, Henderson and Pabis, Modified page equation, Lewis, Weibull, Aghbashlo, Wang and Singh, Midilli, Verma et al., and Thompson models are the most commonly used in the literature dedicated to heat pump dryers.[15,42,75–78] As shown in Table 2, although all of the models cited above fit the experimental data well, Page models and Midili are the models that give satisfactory results and are close to the experimental data, because these two models are efficient for almost different agricultural products tested and of heat pump dryer. Table 2 shows the mathematical models that are currently employed in heat pump drying.

5 | POLICY IMPLICATIONS FOR HEAT PUMP DRYERS

Drying technologies are being developed by scientists all around the world due to their performance. However, due to a lack of defined policies governing their use, the implementation of drying technologies is particularly difficult in developing countries. As a result, few investors are interested in investing in drying technology. Furthermore, certain governments are supporting the fossil fuel industry. Therefore, customers and companies rely on fossil electricity to dry their agricultural products. This problem affects all drying technologies, including heat pump dryers. Another problem is that installing a heat pump dryer in certain countries necessitates getting permission first owing to environmental regulations.[3,82]

6 | NUTRITIONAL COMPOSITION OF DRIED PRODUCTS

Consumer interest in choosing heat pump dryers for the proper or ideal drying of biomaterials depends not only on the efficiency but also on their ability to maintain the

TABLE 2 Mathematical Models of drying kinetics used in heat pump dryers

Authors	Drying system	Product dried	Selected mathematical models	Results
[75]	Vacuum HPD	Sweet basil, parsley and dill leave	Henderson and Pabis, Logarithmic, Two-term model, Modified page equation Lewis	In comparison to other models, the experimental data fit more closely to the logarithmic model, the two-term model, and the Henderson and Pabis model, respectively.
[76]	Solar assisted heat pump fluidized bed dryer integrated biomass furnace and solar assisted fluidized bed dryer integrated biomass furnace	Paddy	Page Newton Henderson and Pabis	It was discovered that Page's model best described the drying behaviour.
[42]	SAHPD	Orthosiphon stamineus Benth	Newton, Page, Modified Page Midilli-Kucuk	The highest goodness of fit was shown by the Page model.
[79]	SAHPD	Red chillies	Newton, Henderson-Pabis, Page models	Results were best with the page model.
[77]	Vacuum HPD	Shiitake mushrooms	Newton Modified Page Approximation of diffusion Wang and Singh ogarithmic Simplified Fick's diffusion Modified Page equation Two-term model Midilli	The drying of Shiitake mushrooms was best predicted by Midilli.
[78]	Closed Loop Heat Pump Assisted Drying	Pineapple	Lewis, Henderson & Pabis, Logarithmic, Page, Midilli & Kucuk, Weibull Aghbashlo	The models developed by Midilli & Kucuk and Aghbashlo et al. accurately predicted the experimental data.
[80]	closed HPD	*Tenebrio molitor*	Page, Wang and Singh, Logarithmic Midilli	The drying curves were adequately described by each model. The Midilli model, which accurately represented *Tenebrio molitor*'s variation in moisture ratio at any time during the experimental period, was the best one.

(Continues)

TABLE 2 (Continued)

Authors	Drying system	Product dried	Selected mathematical models	Results
[81]	HPD	Banana	Lewis, Henderson & Pabis, Logarithmic, Page, Midilli & Kucuk Aghashlo et al.	The model developed by Midilli & Kucuk has the highest degree of correlation, according to the statistical study.
[15]	Direct expansion heat pump assisted solar dryer	Lemon	Newton, Page, Henderson & Pabis, Logarithmic, Two term, Wang and singh, Modified Page Thompson	The most effective model for describing the drying characteristics of lemon slices was found to be two terms and modified Page.
[73]	Closed loop HPD	Tomato	Lewis, Henderson & Pabis, Logarithmic, Verma et al., Page, Midilli et al., Parabolic, Wang and Singh, Weibull Aghbashlo et al.	The models with the best fit was Midilli et al., Aghbashlo et al., and Parabolic.
[74]	Fluidized bed dryer equipped with a heat pump humidifier	Green bell pepper	Newton Logarithmic Page Two-term Wang and Singh Approximation of diffusion Modified Henderson and Pabis Midilli–Kucuk Henderson and Pabis	The Midilli model offered the best correlation with the experimental results.
[72]	Solar-assisted heat pump fluidised bed dryer	Rice	Newton, Henderson and Pabis Page	The result indicated that the experimental moisture rate data fit the Page model adequately.

quality of the dried product. The emphasis in the literature is on colour, as well as all nutritional characteristics of drying materials. Particular attention is therefore paid to the dried products to demonstrate whether the latter has been able to retain all of the properties after drying. Beta-carotenes, vitamin C, phycocyanins, total phenol content, and polysaccharides are among the nutritional parameters frequently assessed in relation to recent studies on heat pump dryers.[34,40,54,61,65,83,84] These bioactive nutrients are highly sensitive to heat that is why they are frequently assessed to assure the quality of dried products.[85] Findings on the nutritional composition of dried biomaterials using heat pump dryers from recently published works are summarized in Table 3.

6.1 | Beta-carotenes

Beta-carotene is sometimes referred to as provitamin A, because one molecule of beta-carotene is transformed into two molecules of vitamin A, when ingested by humans.[90,91] It is therefore necessary to reduce the loss of beta-carotenes during drying. The solar-assisted heat pump dryer used to dry the pumpkin has given good results in reducing losses in beta-carotene content, because the content of beta-carotene in the dried sample was 10.202 mg/g.[40] Good results were also achieved by the solar-assisted heat pump dryer fabricated by Sevik[86] to dry parsley, strawberry, mint, and tomato. The result demonstrated that there was no substantial drop in the content of beta-carotene in dried products. Sanpang et al.[87] dried kaffir lime leaves with a heat pump dryer. The maximum beta-carotene of kaffir leaves content was found among the dried samples at 55°C, with a value of 1.66 mg/g. However, at 45°C and 50°C, the beta-carotene value was 1.17 and 1.28, respectively.

6.2 | Vitamin C and total phenols content (TPC)

Vitamin C, which is found mostly in fruits and vegetables, is frequently used to assess the nutritional content of these foods. Indeed, due to its high sensitivity to many physicochemical parameters including temperature, pH, light, the presence of oxygen, enzymes, and catalysts, it is a unique witness to the severity of any degradations that may have occurred during processing. The loss of vitamin C during the drying process could be induced by high temperatures or a long drying time.[59,83,92] However, TPC is a secondary metabolite that is produced spontaneously during soaking and germination, and antioxidant capabilities are found in phenolic compounds.[93–95] To enhance the drying quality of biomaterials, Lee et al.[54] developed a Coulomb force-assisted heat pump dryer. According to findings, this dryer preserved total phenolic content and the bulk of the vitamin C in dried lemon. The quantity of vitamin C was found to be 2.5–93.2% higher than in oven-dried samples. Liu et al.[65] obtained the same results in their studies, demonstrating that employing contact ultrasound reinforcement in a pump dryer of kiwi fruit slices increased overall phenolic content and vitamin C content. According to the results, the total phenolic content values improved from 220.51 to 240.58 mg/100 g when ultrasonic power increased from 0 to 48 W at 30°C. At 40°C, increasing ultrasonic power from 0 W to 24 and 48 W enhanced vitamin C content by 11.1% and 20.3%, respectively. Kaffir leaves were dried by Sanpang et al.[87] to illustrate the ability of a heat pump dryer to preserve the total phenol content. The total phenolic content of Kaffir leaves was 43.03 mg/g GAE before drying, but after drying, the amounts were 14.56, 17.34, and 16.71 mg/g GAE at 45°C, 50°C, and 55°C, respectively.

6.3 | Phycocyanins

Phycocyanins have bioactive compounds which have antioxidant, anticancer and anti-inflammatory properties. It is therefore necessary to ensure that the drying operation does not affect these bioactive compounds properties. Thus, the heat pump dryer was used by Costa et al.[84] to dry spirulina sp. According to the findings, the air temperature had the greatest impact on the phycocyanin content. To compare a traditional tray dryer and heat pump dryer, the drying of Spirulina was done by Costa et al.[88] Results showed that heat pump dryers with an air temperature of 50°C preserved the Spirulina properties the best, and the values of phycocyanin were 14% greater in this condition than in the same situation for the conventional tray dryer.

6.4 | Polysaccharides

Polysaccharide analysis is especially crucial since these macromolecules are responsible for a wide range of physicochemical and sensory phenomena. For drying ganoderma lucidum, radio frequency technology was integrated with a heat pump dryer by Hay et al.[61] Results showed that increasing radio frequency power retained more polysaccharide after drying. The polysaccharide content was 7.82, 9.18, 9.31 and 9.47 mg/g, when the radio frequency power

TABLE 3 Nutritional content results

Authors	Drying system	Country	Product dried	Vitamin C (Preserved)	Polysaccharide (Preserved)	Phycocyanin (Preserved)	Total phenolic content (Preserved)	β-carotene (mg/g) (Preserved)
[83]	Hot air drying	China	Okra	23.79% to 46.25%	73.26% to 88.27%	NA	81.85% to 96.12%	NA
	HPD	China	Okra	29.52% to 72.23%	82.78% to 94.1%		85.44% to 97.54%	
[84]	HPD	Brazil	Spirulina	NA	52.6%	19.6 mg/g	NA	NA
[40]	SAHPD	China	Pumpkin slice	25.682 mg/100 g dried sample	NA	NA	NA	10.202 mg/g
[54]	CFAHPD	Malaysia	Lemon slices	0.00674 kg	NA	NA	10.14 ± 0.37 kg Gallic Acid/kg dry weight	NA
[65]	UAHPD	China	Kiwifruit	When ultrasonic powers were increased, the values increased between 11.1% and 20.3% at 40°C.	NA	NA	From 220.51 to 275.23 mg/100 g	NA
[34]	HPD	Turkey	Grape pomace	NA	NA	NA	55.6 ± 4.0 (mg Gallic Acid Equivalent/g dry weight)	NA
[61]	RFAHPD	Vietnam	Ganoderma lucidum	NA	7.82, 9.18, 9.31 and 9.47, when the radio frequency power was 0, 0.65, 1.3 and 1.95, respectively.	NA	NA	NA
[86]	Solar-HPD	Turkey	Tomato, straw-berry, mint, and parsley.	Tomato: 83% Strawberry: 65.2%	NA	NA	Tomato: 2% Mint and parsley: from 13.5% to 18.4% Strawberry: 35%	No substantial drop
[87]	Heat pump, heater and hybrid systems dryer	Thailand	Kaffir lime leaves	NA	NA	NA	14.56, 17.34, and 16.71 mg/g Gallic Acid Equivalent respectively at 45, 50, and 55°C.	1.66, 1.17 and 1.28 respectively at 55, 45°C and 50°C

TABLE 3 (Continued)

Authors	Drying system	Country	Product dried	Vitamin C (Preserved)	Polysaccharide (Preserved)	Phycocyanin (Preserved)	Total phenolic content (Preserved)	β-carotene (mg/g) (Preserved)
[88]	HPD	Italia	Spirulina sp.	NA	NA	14%	60%	NA
[89]	Hot Air Drying and Heat pump drying	China	Gastrodia elata	NA	16.39 and 16.52 respectively, in the hot air and heat pump dried samples	NA	NA	NA

was 0, 0.65, 1.3 and 1.95 kW, respectively. Huang et al.[96] compared physicochemical and immunomodulatory characteristics of polysaccharide–protein complexes from vacuum microwave, vacuum freeze, and heat pump dryer for drying litchi pulp. Heat pump dryer proved to be the most effective way for improving the immunomodulatory characteristics of litchi pulp. Cheng et al.[89] dried fresh Gastrodia elata using hot air drying and heat pump drying methods. The drying temperature for both methods was 50°C. The findings reveal that none of the drying methods had any influence on the polysaccharides in the samples. With values of 16.39 and 16.52, respectively, the mean polysaccharide values in the hot air and heat pump-dried samples were practically identical.

7 | COLOUR ANALYSIS

Consumer acceptance of agricultural products is influenced by colour.[97,98] Colorimeters are tools that are used to determine the colour of foodstuffs. They use three major colour sensors to detect the light reflected from an object: red, green, and blue, which have the same sensitivity as human eye receptors.[99,100] Despite the fact that there are many other colour spaces for determining the colour of objects, the CIELAB colour space, also referred to as $L^*a^*b^*$ is the widely used when it comes to food because of its uniform colour distribution and colour perception that is closest to that of a single human eye. To properly measure all perceptible colours, CIELAB employs three colour values. Each of the three values used by the CIELAB is represented by the letters L^*, a^* and b^*. The L^* measures the whiteness value of a colour and ranges from black to white. b^* measures blue when negative and yellow when positive. a^* measures green when negative and red when positive.[101,102] There are also other derived parameters such as total colour change (ΔE) and chroma (c^*).[103]

Regardless of the type of dryer employed, most research on the drying of plants, fruits, and vegetables spends a significant portion of their research on colour analysis, and heat pump dryers are no exception according to the results found, heat pump dryers improve the colour better compared to other systems. Haonan et al.[104] compared a heat pump dryer and hot air drying to dry jujube slices. Based on the results, the quality of jujube slices was improved by using a heat pump dryer, which increased the lightness value while decreasing the total colour difference value. Using an open-loop batch-type heat pump dryer to dry coffee, Fernando et al.[29] concluded that the colour of coffee did not change significantly.

Results showed that, compared to fresh coffee, the total colour difference value for coffee at 10.11% moisture content was 31.65. The drying of bananas investigated in a closed loop heat pump dryer system by Tunckal et al.,[81] showed that the colour values of redness and the total colour difference increased, whereas those of lightness and yellowness decreased as the drying temperature increased. The total colour difference increased from 30.71 to 31.04 as the drying temperature increased from 37°C to 43°C. The effects of heat pump drying on colour change and nitrite content changes were investigated by Gan et al.[103] It was discovered that using an intermittent heat pump dryer with a longer tempering duration or lower intermittency reduced the nitrite level of edible bird's nest and enhanced the colour change. Results revealed that drying edible bird's nest using a heat pump at 28.6°C reduced the overall colour change by 76%. Gan et al.[42] compared solar-assisted heat pump drying to solar drying to evaluate the drying kinetics and product quality of misai kucing. Because of the chlorophyll degradation, when compared to solar-assisted heat pump-dried samples, solar-dried samples presented the highest overall colour change. Yam chips were dried at 500, 1000, and 2000 W using a heat pump dryer alone or with far infrared radiation. The yam chips dried with a heat pump dryer coupled with far infrared radiation were lighter and had similar redness and yellowness to the heat pump-treated samples. The dried Chinese yam chips had reduced shrinkage, better rehydration ability, lower hardness, and higher brittleness than the others when dried in a heat pump dryer using far infrared radiation at 1000 W.[49] The results of colour analysis are summarized in Table 4.

8 | TECHNO-ECONOMIC ANALYSIS

Techno-economic analysis examines the development of technology and research projects based on risks, benefits, uncertainties, costs, and time frames with the aim of evaluating the economic impacts of a novel technology.[108] Heat pump dryers have been examined in detail by many researchers. Furthermore, there is limited literature addressing the techno-economic aspects of these systems. Meyer et al.[109] in one of the few studies on the subject, conducted an economic analysis of the heat pump dryer in comparison to alternative heating systems. The life cycle costs of heat pump dryers were found to be more economical. Similarly, in a comparative study between a solar-assisted heat pump dryer and a heat pump dryer, the solar-assisted heat pump dryer had a higher initial cost but a low operating cost according to Singh et al.[38]

As the payback period is one of the major techno-economic parameters, many authors pay particular attention to it and the results vary from one study to another. The study conducted by Yahya et al.[72] on a solar-assisted heat pump fluidized bed dryer integrated with a biomass furnace for rice drying has concluded that heat pump dryers can also have such a short payback period of around 1.6 years. This is also the case of the photovoltaic/thermal assisted-heat pump drying system developed by Koşan et al.[51] which gave a payback of 2.32 years. The waste heat recovery-assisted heat pump dryer in the closed-loop developed by Singh et al.[66] also gave a short payback period which was found to be 2.75 years. These payback periods provide accurate information on public acceptance of heat pump dryers.

According to what has already been stated, there are relatively few techno-economic research available in the literature regarding heat pump dryers. Table 5 summarizes the findings obtained from the techno-economic analysis of the studies mentioned above. Among all of the major parameters presented, this table confirms that the payback period has received a lot of attention, but the net present value and the return on capital have received the least attention. As a result, it is difficult to get a general idea of the economic consequences associated with each type of heat pump dryer currently available at this time.

9 | EXERGOECONOMIC ANALYSIS

Exergoeconomic is a method based on exergy that determines the location, amount, sources, and cost of thermodynamic inefficiencies in an energy-conversion system.[110–113] The cost of exergy destruction, system recovery factor and exergoeconomic factor are the major parameters for the exergoeconomic analysis.

Singh et al.[38] used exergoeconomic analysis to anticipate the cost of exergy destruction and the cost of component inefficiencies in the system. On this, the authors developed the convective closed-loop solar-assisted heat pump dryer to dry banana chips. According to the results, the expansion device had the lowest exergoeconomic factor. The results showed also that, the components that require the most improvement were the evaporator and the expansion device based on the exergoeconomic factor. Another study investigated by the same author examined the exergoeconomic parameters of the heat pump dryer

TABLE 4 Colour analysis results

Authors	Drying system	Country	Product dried	Drying temperature (°C)	Colour parameters: Lightness (L*) Initial	Lightness (L*) Final	Redness/greenness (a*) Initial	Redness/greenness (a*) Final	Yellowness/blueness (b*) Initial	Yellowness/blueness (b*) Final	Total colour difference (△E) Initial	Total colour difference (△E) Final
[104]	HPD	China	Jujube	60	44.7	38.1	13.6	15.1	24.5	20.6	0	3.7
[105]	HPD	Brazil	Spirulina SP.	50	NA	21.9 ± 0.5	NA	−3.68 ± 0.09	NA	7.44 ± 0.09	0	5.71 ± 0.18
[103]	HPD	Malaysia	Edible Bird's Nest	28.6	58.7 ± 2.62	59.6 ± 1.54	0.80 ± 0.21	0.80 ± 0.09	12.1 ± 2.85	16.7 ± 0.92	0	4.74 ± 5.02
[42]	SAHPD	Malaysia	Misai Kucing leaves	33.1 ± 0.24	30.00 ± 0.26	42.30 ± 0.43	−5.10 ± 0.35	− 7.20 ± 0.12	3.50 ± 0.36	4.80 ± 0.38	0	18.29 ± 0.11
			Misai Kucing flowers	35.3 ± 0.19	33.00 ± 0.37	33.70 ± 0.46	7.40 ± 0.12	8.20 ± 0.24	5.00 ± 0.42	7.80 0 ± 0.31	0	21.23 ± 0.23
			Misai Kucing stems	34.6 ± 0.14	30.00 ± 0.16	30.40 ± 0.10	−6.40 ± 0.09	−6.60 ± 0.37	11.10 ± 0.54	11.60 0 ± 0.43	0	2.72 ± 0.64
			Misai Kucing mix	34.9 ± 0.09	36.00 ± 0.21	34.90 0 ± 0.24	−6.80 ± 0.36	−5.00 ± 0.19	4.90 ± 0.27	6.50 ± 0.22	0	17.26 ± 0.25
[49]	HPD	China	Chinese Yam	50	78.67	58.90 ± 1.87	−3.13	5.19 ± 0.42	10.17	26.39 ± 0.90	0	26.89 ± 0.79
	HPD combined with far infrared radiation at 1000 W	China	Chinese Yam	50	78.67	66.98 ± 1.45	−3.13	3.98 ± 0.25	10.17	28.17 ± 0.99	0	22.61 ± 0.62
[106]	HPD	Sri-lanka	Coffee	56.9 ± 2.2	49.14 ± 3.79	32.60 ± 3.44	12.35 ± 3.49	6.18 ± 3.72	29.39 ± 3.59	9.77 ± 3.51	0	31.65
[107]	HPD	Turkey	Banana	37	88.63	62.36	2.28	2.54	32.48	28.39	0	30.71
				40	88.63	61.32	2.28	2.72	32.48	28.15	0	30.73
				43	88.63	59.87	2.28	3.06	32.48	27.48	0	31.04
[61]	RFAHPD (Radio frequency power = 1.95 kW)	Vietnam	Ganoderma lucidum	45	47.12	39.35	4.11	5.12	18.85	14.46	0	8.98

(Continues)

TABLE 4 (Continued)

Authors	Drying system	Country	Product dried	Drying temperature (°C)	Colour parameters							
					Lightness (L*)		Redness/greenness (a*)		Yellowness/blueness (b*)		Total colour difference (△E)	
					Initial	Final	Initial	Final	Initial	Final	Initial	Final
	RFAHPD (Radio frequency power = 1.3 kW)	Vietnam	Ganoderma lucidum	45	47.12	39.02	4.11	5.42	18.85	14.1	0	9.48
	RFAHPD (Radio frequency power = 0.65 kW)	Vietnam	Ganoderma lucidum	45	47.12	38.71	4.11	5.75	18.85	13.76	0	9.97
	HPD	Vietnam	Ganoderma lucidum	45	47.12	36.5	4.11	6.94	18.85	12.52	0	12.68

TABLE 5 Techno-economic analysis results

Authors	Country	Drying system	Initial cost ($)	Capital cost ($)	Operating cost ($)	Production cost ($)	Installation cost ($)	Profit or benefit (yearly) in ($)	Return of capital	Payback period (years)	Net present value ($)
[38]	India	HPD	556.89	NA	1565	NA	138.98	NA	NA	NA	NA
		SAHPD	928.52	NA	1470	NA	166.04	95	NA	3.9	NA
[72]	Malaysia	SAHPD with biomass furnace	NA	2550	NA	28,902.25	NA	1528.74	NA	1.6	8563.82
[51]	Turkey	PVTAHPD	NA	NA	NA	NA	NA	NA	NA	2.32	NA
[66]	India	HPD	521.31	NA	2238	NA	NA	NA	NA	NA	NA
		HPD with WHR	864.46	NA	2112	NA	NA	NA	NA	2.75	NA

with and without waste heat recovery.[66] The dryer was manufactured with the purpose of drying radish chips. The results showed that expansion devices had the lowest exergoeconomic factor in both systems. Total exergy destruction costs were 0.10148$/h with a waste heat recovery system and 0.1266$/h without one. In addition, the results showed that the drying chamber was the most essential component that required to be improved depending on the exergoeconomic factor. The batch-type solar-assisted heat pump dryer that Singh et al.[114] investigated for drying bananas in both simple heat pump dryer and solar-assisted heat pump dryer modes revealed that the expansion device in both modes, with calculated values of 0.1395 and 0.2053, respectively, had the lowest exergoeconomic factors. The total cost of energy destruction for the simple heat pump dryer and the solar-assisted heat pump dryer was 0.1185 and 0.1386$/h, respectively. According to the results, it has been shown that the expansion device and evaporator are the most crucial parts that require improvement. The convective closed-loop solar-assisted heat pump dryer, the batch-type solar-assisted heat pump dryer and the simple heat pump dryer with and without waste heat recovery are currently not the only heat pump dryers that have aroused interest in carrying out an exergoeconomic study. Erbay et al.[115] assessed the exergoeconomic performance of a ground source heat pump system utilized in food drying. In this study, the condenser was found to be the essential component in terms of efficiency improvement with a total cost rate of 1.347$/h and an exergoeconomic factor of 0.029. The majority of the condenser's exergy expenses were generated during operation.

This emphasizes the need of conducting exergoeconomic studies because they allow understanding the efficiency of systems and play a key part in systems optimization. Table 6 summarizes the findings of the exergoeconomic analyses conducted on the research listed above.

10 | LIFE CYCLE ANALYSIS (LCA)

Solar energy systems are more environmentally friendly than systems that use traditional energy sources. The noticeable trend of solar energy systems must often contend with the possibility of negative environmental consequences. Some of the environmental considerations for solar energy systems include effects on soil, air, and water; impacts on animals and vegetation; and potentially hazardous material consequences.[116–118] These potential issues appear to be significant barrier to some consumers' future use of these systems.

In this context, LCA therefore appears to be an essential step before placing a solar energy system in the market to develop solar systems that are more considerate to the respectful of the environment. LCA is used to examine the overall impact of a product on the environment during all stages of its life. LCA is usually given in terms of emissions of greenhouse gases.[119,120] It is generally accepted that it provides a better understanding of the impacts of different products on the environment through identification of materials and energy utilized as well as environmental emissions. Kylili et al.[121] used a life cycle assessment to evaluate the environmental impact of industrial solar thermal systems. According to the life cycle assessment findings, the system manufacturing phases and the extraction of raw material, as well as the use phase, are the most environmentally damaging phases of the evaluated solar thermal systems. Moreover, result showed that, in the areas of ozone and element depletions, and human health ecotoxicity, as well as marine and terrestrial environments, the system manufacturing phases and the extraction of raw material are accounted for more than 85% of the total impact.

Oirschot et al.[122] carried out a LCA of two productions of dried seaweed. An impact assessment was conducted with 10 impact categories namely abiotic depletion, terrestrial ecotoxicity, climate change, human toxicity, ozone layer depletion, marine aquatic ecotoxicity, freshwater aquatic ecotoxicity photochemical oxidation, acidification and eutrophication. According to the findings, the seeding lines contributed little to the overall impacts. Harvesting and transport contributed less than 5% to almost all impact profiles, except for acidification and eutrophication, where they contributed 6% and 7% respectively. Both the drying process and the infrastructure contributed to over 70% of each impact category, but not equally. Therefore, studying the LCA of agricultural drying systems helps to provide information on which component of the drying system has the most environmental load and the possibility of improving its environmental performance.[123] However, LCA studies of heat pump dryers are practically non-existent, hence the interest in making an important contribution at this level to have a global view of the consequence linked to the development of heat pump dryers.

TABLE 6 Exergoeconomic analysis results

Authors	Country	Drying system	Components	Cost of exergy destruction ($/h)	System recovery factor (W/$)	Exergoeconomic factor
[38]	India	HPD	Compressor	0.0212	1.139	0.6061
			Condenser	0.00710	0.562	0.7922
			Capillary tube	0.00651	13.12	0.1335
			Evaporator	0.01804	1.7878	0.4902
			Drying chamber	0.00268	0.318	0.8026
		SAHPD	Compressor	0.03104	1.6267	0.6124
			Condenser	0.007132	0.549	0.8153
			Capillary tube	0.005001	10.1	0.2003
			Evaporator	0.01688	1.623	0.6075
			Drying chamber	0.002764	0.4272	0.8515
			Water–air heat exchanger	0.010	1.512	0.611
[66]	India	HPD	Compressor	0.02716	1.426	0.6286
			Condenser	0.0232	1.846	0.566
			Expansion device	0.01187	24.16	0.0918
			Evaporator	0.0217	2.1256	0.5318
			Drying chamber	0.0174	2.666	0.475
		HPD with heat recovery	Compressor	0.03304	1.7348	0.668
			Condenser	0.0197	1.568	0.705
			Expansion device	0.0118	24.02	0.1348
			Evaporator	0.0198	1.942	0.659
			Drying chamber	0.0147	2.2527	0.625
			Cross-flow heat exchanger	0.01246	1.986	0.654
			Heat recovery unit	0.01568	0.4706	0.3407
[115]	Turkey	GSHPD	Compressor	0.007	0.212	0.875
			Condenser	1.308	1.095	0.029
			Expansion valve	0.176	1.769	0.097
			Evaporator	0.610	0.481	0.135
			Pump	0.004	0.330	0.819
			GHE	0.047	0.049	0.759
			Drying cabinet	0.480	0.147	0.086
			Drying duct	1.095	1.359	0.010
[114]	India	HPD	Compressor	0.0336	1.146	0.6065
			Condenser	0.02816	0.566	0.7982
			Expansion device	0.001067	13.39	0.1395
			Evaporator	0.018	1.7978	0.4952
			Dryer chamber	0.0115	0.308	0.8076
			Solar heat exchanger	-	-	-

TABLE 6 (Continued)

Authors	Country	Drying system	Components	Cost of exergy destruction ($/h)	System recovery factor (W/$)	Exergoeconomic factor
		SAHPD	Compressor	0.05017	1.6327	0.6174
			Condenser	0.0331	0.557	0.8203
			Expansion device	0.00129	10.2	0.2053
			Evaporator	0.02689	1.673	0.6115
			Dryer chamber	0.01719	0.4312	0.8595
			Solar heat exchanger	0.01655	1.582	0.621

11 | CONCLUSIONS

The objective of this study was to evaluate the performance of different types of heat pump dryers used to dry biomaterials. The study also investigated the effects of heat pump dryers on the colour and nutritional content of dried products. In addition, the impacts of heat pump dryers on the environment as well as their exergoeconomic and economic consequences, which are generally neglected in reviews dedicated to heat pump dryers, were examined. The study also discussed, in brief, the political and regulatory issues related to the development of heat pump dryers, which in particular revealed that governments and investors must collaborate closely to overcome some obstacles that prevent the implementation and most importantly, the promotion of heat pump dryers. Overall, according to the study, heat pump dryers performed well in almost all of the studies reviewed. The various heat pump dryers investigated have demonstrated their efficiency in drying biomaterials. Regardless of the initial high moisture content of the agricultural product, heat pump dryers examined were able to significantly reduce drying time, and achieve high coefficients of performance and specific moisture extraction rates, which reflects the low energy consumption of these systems. Results of the analysis of the drying kinetic models showed that the Page and Midili models are the models that offer excellent results for all the agricultural products examined. According to findings on nutritional composition beta-carotenes, vitamin C, phycocyanins, total phenol content, and polysaccharides are among the bioactive components extremely sensitive to heat that are commonly assessed to ensure the quality of dried products. Heat pump dryers contribute strongly to retain all the bioactives mentioned but also heat pump dryers have the capacity on colour retention. Results also showed that there is relatively few techno-economic and exergoeconomic studies available in the literature regarding heat pump dryers. According to the findings, the expansion valve has the minimum exergoeconomic factor of all heat pump components, while the compressor has the highest cost of exergy destruction in general. The net present value and return on capital have received the least attention of any of the major techno-economic parameters studied. The payback period, on the other hand, has received a lot of attention, and most developed heat pump dryers have a very short payback period. Therefore, there is still some uncertainty about environmental consequences of heat pump dryers because research on environmental impacts or LCA is almost non-existent. Hybrid heat pump dryers are a better alternative since they provide the customer the flexibility to select a variety of drying modes based on the energy available, such as with solar-assisted heat pump dryers, despite having slightly higher manufacturing costs than other technologies but they provide high energy efficient and dried products of high quality.

12 | RECOMMENDATIONS

The following are our recommendations for future research on heat pump dryers:

1. Design simple and low-energy heat pump dryers that will reduce manufacturing costs and electricity bills, and make maintenance easier.
2. Propose a comprehensive study of the performance of heat pump dryers using all of the parameters that compose the kinetic, energy, and exergy analyses, to better illustrate heat pump dryers' efficiency.
3. Carry out comprehensive research on the life cycle, techno-economic and exergoeconomic analyses of heat pump dryers which might respectively provide a global view of the environmental and economic consequences of heat pump dryers and help to know the components to be optimized in the system.

NOMENCLATURE

ASHPD	air source heat pump dryer
a*	redness/greenness
b*	yellowness/blueness
CFAHPD	Coulomb force assisted heat pump dryer
COP	coefficient of performance
db	dry basis
GAE	gallic Acid Equivalent
GSHPD	ground Source Heat pump drye
GSHPD	ground Source Heat pump drye
h	hour
HPD	heat pump drye
HRU	heat recovery unit
IAHPD	infrared assisted heat pump dryer
ICHPDS	independent closed heat pump drying system
ISDC	independent solar drying system
kg	kilogramme
kW	kilowatt
kWh	kilowatt-hour
L*	lightness
m	metre
min	minute
PVAHPD	photovoltaic assisted Heat pump drye
RF	radio Frequency
RFAHPD	radiofrequency assisted heat pump dryer
s	second
SAHPD	solar assisted heat pump dryer
SIAHPD	solar infrared assisted heat pump dryer
SMER	specific moisture extraction rate
UAHPD	ultrasound-assisted heat pump dryer
W	watt
wb	wet basis
WHR	waste heat recovery
WHR-HPD	waste heat recovery heat pump dryer
$	dollar
%	percentage
°C	degree celsius
▵E	total colour difference

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