CHAPTER 2

LITERATURE REVIEW

In this chapter, literature on the heat pump dryer related to the simple heat pump dryer and hybrid source heat pump dryer is considered (theoretical and experimental work). The available open literature is divided into the four subsections for an easy understanding of the research gap, the first part contains the theoretical work done on a simple heat pump dryer, the second part contains the experimental work done on a simple heat pump dryer, the third part contains the theoretical work done on hybrid source heat pump dryer and fourth part contains the experimental work done on hybrid source heat pump dryer. Finally, the research gap and the objective of the current study are presented in this chapter.

2.1. Theoretical studies on simple heat pump dryer

Theoretical analysis of any system is done by applying the different mathematical models and solving the models by using different techniques and software. Theoretical analysis can be easily done as compared to the experimental analysis, which needs the design, development, and performance analysis of the experimental setup. The main advantage of applying the theoretical analysis is the reduction in the cost of the analysis. Many open works of literature are available on theoretical analysis of the simple heat pump dryer.

Schmidt et al. (1998) numerically compared the performance of the heat pump dryer using the CO_2 as a natural refrigerant with the R134a refrigerant. The authors concluded the better performance with the CO_2 heat pump dryer compared to the R-134a. Ogura and Mujumdar (2000) proposed the concept of a new eco-friendly chemical heat pump dryer that uses chemical energy in the heat pump. Achariyaviriya et al. (2000)

developed a mathematical model and perform the simulation using the moisture content of the papaya glace and also the simulation results were validated with the experiment. The simulation was done at a drying air temperature of 45°C, 10.3 kg/h of flow rate, and 70% of ambient relative humidity. The author concluded that the SMER decreases with an increase in the ambient humidity and temperature. Adapa et al. (2002) developed a simulation model of the heat pump dryer and validated the model with the experimental data for the drying of the chopped alfalfa in the temperature range of 30-45°C. Braun et al. (2002) numerically compared the performance of the air heat pump dryer (which works on the reverse Brayton cycle) with the conventional electric heater dryer for the clothes drying using the EES software and considered the air temperature at the inlet and outlet of drum dryer as 118°C and 38°C. The authors concluded that the improvement in energy efficiency was 40% over the conventional electric heater at an airflow rate of 110kg/h with an ambient relative humidity of 60%. Teeboonma et al. (2003) developed a mathematical model to study the optimum range of the different parameters such as recirculation ratio, by-pass ratio, and the drying air temperature for the fruit drying with the heat pump dryer and suggested a mathematical model for the mango and papaya slice drying. The author estimated the optimum drying condition for the papaya as 69% by-pass ratio, 100% recirculation ratio, 55°C air temperature, and 20.72kg/h air flow rate and for mango, it was like 71% by-pass ratio, 100% recirculation ratio, 55°C air temperature, and 30.88 kg/h air flow rate. Saensabai and Prasertsan (2003) studied the optimum operating mode of a heat pump dryer in different five modes within the ambient temperature range of 20-40°C. The authors observed that the drying rate and the ambient conditions mostly affect the operating mode of the heat pump dryer. Sarkar et al., 2006, numerically studied the heat pump dryer using the natural CO_2 gas as a refrigerant to investigate the performance of the system in different bypass air ratios and the air recirculation ratio with different drying ambient temperatures (20-40°C), relative humidity (30-70%), efficiency and the mass flow rate of air. The author concluded that both SMER and the COP decrease with an increase in both bypass ratio and the air recirculation ratio. Soylemez et al. (2006) developed a mathematical model for the study of the heat pump drying system with heat recovery using thermodynamic economic methods to obtain the optimum operating condition of the system.

Pal and Khan (2008) presented the various design steps for the heat pump dryer (batch type) and calculated the different performance parameters for different drying air temperatures (30°C, 35°C, 40°C) and relative humidity (30%, 20%, 15%). The calculated values of SMER and COP of the system were 1.84kg/kWh and 4.1 respectively at a drying temperature of 40°C and relative humidity of 15%. Le et al. (2008) carried out the thermal and economic analysis of the absorption heat pump dryer for the wood chips drying. The considered drying temperature was 100°C. Ceylan and Aktaş (2008) used the artificial neural network to estimate the errors in the experimental results in the heat pump dryer for the hazelnuts at different velocities, moisture content, and drying air temperature. Li et al. (2009) numerically investigated the CO_2 heat pump dryer and compared the result of the two-stage heat pump dryer with the single stage. The author concluded that the MER was much higher for the two-stage as compared to the single stage. Lee and Kim (2009) performed the simulation of the heat pump dryer to obtain the various design parameters of a box-type dryer and validated the simulation result with the experimental for the radish dying. The simulation analysis of the system was carried out by considering the ambient temperature, relative humidity, and air flow rate of 20°C, 100%, and 30m^3/min respectively. The SMER and the COP were calculated as 3.64kg/kWh and 3.75 respectively at a drying chamber inlet temperature of 44.7°C. Minea (2010) developed a mathematical model to predict the error in the design of the heat pump dryer which is responsible for the variation in the condenser and evaporator saturation pressure with damage to the compressor also. The author suggested the various correlation and methods for proper operation of the system. Lee et al. (2010) carried out the performance simulation of the tow stage heat pump dryer using the two different refrigerants (R-124, R-134a) in two different refrigeration cycles to get the high temperature (greater than 80°C) drying air. Also evaluated the various performance parameters of the heat pump dryer such as COP of high and low-temperature refrigeration cycle as 3.33 and 4.53 with SMER greater than 3.5kg/kWh and MER as 45.51kg/h. Rezk and Forsberg (2011) developed a numerical model and analyzed it by using CFD software comsol to reduce the energy consumption in the heat pump drying system. Cotton et al. (2011) studied the heat pump dryer by developing a mathematical model to evaluate the system performance in isothermal and adiabatic modes using energy, exergy, and economic methods. SMER and MER were calculated as 21.2kg/h and 4.2kg/kWh and for isothermal as 55.4kg/h and 13.7kg/kWh. Hii et al. (2013) investigated the kinetics of the cocoa beans drying with a heat pump dryer using the computer simulation at a constant drying temperature of 56°C. The author analyzed the effect of the shrinkage on the kinetics analysis but found a negligible effect. Hossain et al. (2013) developed a mathematical model to evaluate the performance of the heat pump dryer for aromatic plant drying. The average drying air relative humidity and the temperatures were 20% and 36.84°C respectively and the drying time was 89 hours to reduce the moisture content from 89 to 9% (w.b.) for valerian roots. The authors calculated the values of COP, SMER, and MER as 5.45, 0.038kg/kWh, and 140.03kg/h respectively.

Bengtsson et al. (2014) developed a simulation model of a heat pump tumble dryer to investigate the effect of the compressor cylinder volume and the heat exchange in the condenser on the drying time and the energy consumption in the system and the simulation model was validated with the experimental results. The author concluded the reduction in drying time by 14% and an increase in energy consumption by 14% with an increase in cylinder volume by 50%. Erdem and Heperkan (2014) theoretically investigated the heat pump tumble drying with natural CO_2 refrigerant using MATLAB computer software, and the dependency of the various parameters on the energy consumption and the drying time was estimated. The author concluded that the optimum values of operating parameters (CO_2 inlet-outlet pressure and temperature to the condenser and evaporator) help to reduce the drying time and the energy consumption. Bockholt et al. (2016) studied the tool chain structure of the heat pump tumble dryer. TeGrotenhuis et al. (2017) developed a mathematical model for a new hybrid heat pump clothes dryer to increase the electric energy savings by 50% and concluded the COP of 2.5 at a drying temperature of 50°C in the dryer drum exhaust. Wang et al. (2018) carried out the analysis of the heat pump dryer with heat recovery using air to the air heat exchanger and heated the ambient air to 200°C and studied the different refrigerants to analyze the heat recovery with lower energy consumption. The author concluded that the R134a was the most promising refrigerant as compared to others in terms of energy efficiency. Holtkotter et al. (2018) studied the rapid controlling of the heat pump dryer for clothes drying. Sian and Wang (2019) numerically studied the CO_2 and R-134a heat pump dryer for clothes drying at ambient temperature and relative humidity of 25°C and 80%. The authors concluded that the CO_2 is having higher drying temperature as compared to the R-134a and also has higher SMER and COP. Brandt et al. (2019) carried out the simulation and experimental validation of the heat pump tumble dryer using the R-744 refrigerant and compare the result with other different refrigerants. Lee et al. (2019) developed a simulation model to study the performance of the heat pump tumble clothes dryer using the different design parameters of the components. Jokeil et al. (2020)

developed a numerical model and validated it with an experiment to study the heat pump dryer for the drying of the organic products using the CO_2 as a working refrigerant at a darting temperature of 50-70°C. It was concluded from the model that the closed-loop heat pump dryer is having 84 % more energy saving compared to the open-loop system and SMER was 4 times higher in a closed-loop system. Dai et al. (2020) developed a simulation model to study the thermodynamic and environmental potential of the heat pump dryer using the R-32and CO_2 mixture as working refrigerants.

Table: 2.1. Literature review on numerical analysis of simple heat pump dryer

Author	Drying product	Refrigerant	Drying temperature	Findings
Schmidt et al. (1998)	…………	CO_2, R-134a	60°C	Better performance with CO_2 heat pump dryer compared to the R-134a.
Ogura and Mujumdar (2000)	………..	……..	50°C	The energy and exergy efficiency mostly depends on the chemical reaction.
Achariyaviriya et al. (2000)	Papaya glace	………	50°C	SMER decreases with an increase in the ambient humidity and temperature.
Adapa et al. (2002)	Alfalfa	R-134a	30-45°C	SMER was between 0.5 and 1.02kg/kW-h.
Braun et al. (2002)	Clothes	Air	118°C	The improvement in energy efficiency was 40% compared to the conventional electric heater.
Teeboonma et al. (2003)	Mango, papaya	R-22	55°C	The optimum drying condition was not the

				same for both products at same.
Saensabai, and Prasertsan (2003)	……….	R-22	20-40°C	HPD is suitable for a continuous dryer at constant dryer efficiency.
Sarkar et al. (2006)	………..	CO_2	55-73°C	Drying efficiency, RAR, ambient temperature, and airflow rate have more effect on the system compared to humidity and BAR.
Soylemez (2006)	………	……………	25-65°C	Heat pump systems used for drying must be designed close to the optimum point.
Pal et al. (2008)	……..	R-134a	30-40°C	The values of SMER and COP of the system were 1.84 kg/kWh and 4.1 at a drying temperature of 40°C.
Le et al. (2008)	Wood	…………	50-100°C	A heat recovery system is the most efficient and economic option.
Ceylan, and Aktaş (2008)	Hazelnut	………	40-50°C	The average error was found as 0.00653 for drying time with ANN.
Li et al. (2009)	……….	CO_2	50-60°C	MER was much higher for the two-stage as compared to the single-stage
Lee and Kim (2009)	Radish	R-134a	44.7°C	SMER and the COP were calculated as 3.64kg/kWh and 3.75 respectively.

Minea (2010)	Wood	………	70-95°C	Intermittent methods improve the final quality of the product and reduce the total drying time.
Lee et al. (2010)	………	R-124, R-134a	80°C	COP of high and low-temperature refrigeration cycles were 3.33 and 4.53 with SMER and MER greater than 3.5kg/kWh and 45.5 kg/h.
Rezk and Forsberg (2011)	……….	………..	………..	Design modification shows the improvement in pressure drop in the drying duct.
Cotton et al. (2011)	…….	R-134a	55-70°C	SMER and MER were calculated for adiabatic as 21.2kg/h and 4.2kg/kWh and for isothermal as 55.4 kg/h and 13.7kg/kWh.
Hii et al. (2013)	Cocoa beans	R-22	56°C	Found the negligible effect of the shrinkage on the kinetics analysis.
Hossain et al. (2013)	Aromatic plants	……..	36.84°C	The COP, SMER, and MER as 5.45, 0.038 kg/kWh, and 140.03kg/h respectively.
Bengtsson et al. (2014)	Textiles	R-134a	45-65°C	Reduction in drying time by 14% and increase in energy consumption by 14% with an increase in cylinder volume by 50%.

Erdem and Heperkan (2014)	Clothes	CO_2	………	Inlet CO2 pressure and temperature to the condenser and evaporator have an acceptable effect on energy consumption and drying time.
Bockholt et al. (2016)	Clothes	………	……..	Toolchain-based modeling reduces the modeling efforts.
TeGrotenhuis et al. (2017)	Clothes	R-134a	50°C	Concluded the electric energy savings of 50% and the COP of 2.5.
Wang et al. (2018)	……….	R32, R134a, R22, R290	113°C	Concluded the R134a as the most promising refrigerant as compared to others in terms of energy efficiency.
Holtkotter et al. (2018)	Clothes	………….	…………	Concluded the rapid controlling with optimum values.
Sian and Wang (2019)	Clothes	CO_2, R-134a	25-45°C	CO_2 HPD has a higher drying temperature, SMER and COP, compare to the R-134a heat pump system.
Brandt et al. (2019)	Clothes	R-290, R-744	…………	The highest exergy destruction takes place in the compressor.
Lee et al. (2019)	Clothes	R-134a	30-40°C	Increasing the airflow rate yields a higher COP value and a shorter drying time.

Jokeil et al. (2020)	Organic product	CO_2	50-70°C	Closed-loop HPD has 84% more energy-saving and 4 times SMER compared to the open-loop.
Dai et al. (2020)	…….	R-32, CO_2	………..	The SMER rate was improved.

2.2. Experimental studies on simple heat pump dryer

Experimental study of any system needs more time and investment as compared to the numerical analysis but provides the results of the actual condition and is more acceptable. Numbers of open literature are available containing experimental result data on the simple heat pump dryer. Klocker et al. (2001) experimented to evaluate the performance of the heat pump dryer using carbon dioxide. The authors experimented with the two types of the compressor and presented the result of MER, SMER, and SEC as 5kg/h, 2.05kg/kWh, and 0.49kWh/kg at the temperature of 50°C for the semi-hermetic compressor with the energy-saving potential of 65%. Ogura et al. (2002) experimented to investigate the chemical heat pump dryer (chemical reaction heat source). Oktay (2003) experimented to investigate the performance analysis of the heat pump drying system at the different airflow rates, recirculation ratio, and the bypass air ratio for the drying of the wet wool at a maximum air operating temperature of 50°C with R-22 as a working refrigerant. The COP of the whole system was in the range from 2 to 3.5 and SMER was in the range from 1.5 to 2.8 kg/kWh. Oktay, (2003) investigated the performance of the heat pump-assisted mechanical opener dryer for the wool drying in different modes of the recirculation air ratio and bypass air ratio with air velocity from 0.65 to 1.25m/s. The maximum drying temperature was set as 60°C and the refrigerant was R-22 used in this analysis in the ambient temperature and humidity of 15-20°C and

60% respectively. The SMER was in the range from 0.65 to 1.75kg/kWh and the heating coefficient of performance was from 2.47 to 3.95. Ameen and Bari (2004) investigated the performance of the drying chamber using the waste heat of the air conditioning condenser for clothes drying and the results were compared with the commercial dryer and outdoor natural drying. The authors concluded the drying air temperature was about 40°C and air velocity between 0.4-0.6m/s. in the humid atmospheric condition (temperature =28-29°C, humidity = 82-84%). The drying time (2 h) and the drying rate (0.424 kg/h) were much better as compared to the commercial dryer and outdoor natural drying with negligible energy consumption. Queiroz et al. (2004) investigated the drying kinetics of the tomato slices in a heat pump dryer using R-22 refrigerant and compared the result with electric heater drying. The experiment was done at drying temperatures of 40°C, 45°C, and 50°C, and air velocities of 1.5 and 2.0 m/s. The authors concluded the heat pump's effective COP was between 2.56 to 2.68 and then about 40% energy economy as compared to the electric resistance heater drying. Adapa and Schoenau (2005) designed, developed, and experimentally tested the recirculation heat pump dryer for the drying of the specialty crops and herbs in the temperature range of 30-35°C and concluded the SMER in between 0.06-0.61kg/kWh. Chua and Chou (2005) designed, fabricated, and analyzed the two-stage heat pump dryer for better heat recovery in two evaporators and condensers using the R-22 as the refrigerant. The author concluded that the more heat, up to 35% more can be recovered in a two-stage evaporator as compared to the single stage. Fatouh et al. (2006) designed and developed a heat pump dryer for herb drying using R-134a refrigerant and investigated the drying characteristics and the system performance. Experimental results showed that the system performance was better at a drying temperature of 55°C and air velocity of 2.7m/s. The author concluded that the lower size herb requires lower specific energy consumption and dying time.

Hawlader et al. (2006) studied the heat pump drying of the apple, guava, and potato in two inert environments (nitrogen and carbon dioxide) and compare the result with freeze and vacuum drying. The author observed the effect on surface porosity and color at drying temperature and relative humidity of 45°C and 10%. It was concluded that the modified heat pump dryer is having better food quality and the economy as compared to the freeze and vacuum drying. Hawlader et al. (2006) investigated the kinetics of the Indian ginger drying in a heat pump dryer using normal air, nitrogen, and carbon dioxide as drying medium. The experiment was performed at a drying temperature of 40°C, relative humidity of 10%, and air velocity of 0.7m/s and concluded that better product quality and lower drying time with nitrogen and carbon dioxide as compared to the normal air medium.

Ceylan et al. (2007) carried out the energy and exergy analyses of the heat pump dryer (using R-404A refrigerant) for the poplar and pine timber drying at drying air temperature and velocity of 40°C and 0.8 m/s. The author concluded the values of the drying time, COP, and SMER for the poplar and pine at 60% air recirculation ratio as 70h, 1.86 and 0.243kg/kWh and 50 h, 1.87 and 0.188kg/kWh respectively. Alves et al. (2008) designed and developed a two-stage heat pump dryer for the drying of the protein in a fluidized bed dryer. Shi et al. (2008) conducted an experimental investigation of the heat pump dryer (using R-134a refrigerant) for the drying of the horse mackerel and analyzed the effect of the different parameters on the performance and drying kinetics. The drying air temperature and the air velocity ranged from 20-30°C and 2.0-3.0m/s and the SMER was maximum for the bypass air ratio between 0.6-0.8. Pal et al. (2008) studied the drying of the green sweet pepper in a heat pump dryer at 30°C, 35°C, and 40°C temperature and in a hot air dryer at 45°C with a relative humidity range of 19-55%. It was concluded that the heat pump drying at 40°C required less drying time with a better drying rate and SMER as compared to the hot air drying at 45°C. Phoungchandang et al. (2008) investigated the drying of the Kaffir lime leaf with a tray dryer and heat pump dryer and fitted the different drying models with experimental data for kinetics analysis at drying temperatures of 40°C, 50°C, and 60°C. Phoungchandang et al. (2009) experimentally investigated the performance of the heat pump dryer and compared the result with the tray drying and with the mixed-mode solar drying for the ginger in the temperature range of 40°C, 50°C, and 60°C. Erbay and Icier (2009) experimented to investigate the product quality of the energy potential for the olive leaf drying with a heat pump dryer (using R-407C refrigerant) and optimization of the drying conditions was done using the surface response methodology. The optimum drying air temperature and velocity were 53.43°C and 0.64m/s respectively. Artnaseaw et al. (2010) designed and developed a vacuum heat pump dryer (using R-22 refrigerant) for the chili drying to investigate the effect of the parameters such as temperature (50°C, 55°C, 60°C, 65°C) and pressure (10kPa, 20kPa, 30kPa, 40kPa) on the product quality and drying time. It was concluded that the drying time decreases with a decrease in pressure and increase in temperature of the drying medium and the Midilli model agrees the best for the red chili.

Jinjiang and Yaosen (2010) experimented to study the performance of the heat pump dryer with heat recovery for paddy drying. Chin and Law (2010) compared the intermittent heat pump drying (40.6°C) of Ganoderma tsugae with the freeze-drying (-18°C), convective hot air (50°C) drying, and vacuum drying (50°C). it was found that intermittent drying is having a higher energy efficiency as compared to the other drying methods. Hepbasli et al. (2010) designed and developed a heat pump dryer (using R-407C refrigerant) to investigate the exergoeconomic parameters for the drying of plum slices at drying air temperature between 45-55°C. The ratio of the exergy destruction rates to capital cost varied between 1.668 and 2.063W/$ and its values were found higher for the compressor, evaporator, and heat recovery unit and need to be improved. Wang et al. (2011) studied the performance and economics of the heat pump drying (using R-22 refrigerant) of hawthorn cake and compared the result with the hot air drying. The drying temperature was in the range of 45-56°C for the heat pump and was between 40-70°C for hot air drying. The author found that at the same drying temperature, the drying rate of hawthorn cake was higher for heat pump drying. Phoungchandang and Saentaweesuk (2011) reported that the modified page model is best fitted for the drying of the sliced ginger with the heat pump dryer at drying temperatures of 40 and 60°C. Castell-Palou and Simal (2011) investigated the drying kinetics of the heat pump dryer for the drying of the pressed cheese and fitted it to the models to estimate the correlations. Mancini et al. (2011) compared the experimental and the theoretical results of the CO_2 heat pump dryer with the R-134a HPD for clothes drying. It was found that the CO_2 heat pump dryer performs better with energy-saving as compared to the R-134a. Gungor et al. (2012) experimentally determined the exergoeconomic analysis of the gas engine-driven heat pump dryer for the drying of the medicinal and aromatic plants and studied the effect of the various dead state temperature on the exergoeconomic parameters. Senadeera et al. (2012) carried out the experimental investigation of the two-stage heat pump drying of the bovine intestine in a fluidized bed dryer and it was concluded that the drying kinetics was mostly affected by temperature. Ong et al. (2012) studied the intermittent drying of the salak fruits with the heat pump dryer at different intermittent ratios and concluded that intermittent drying reduces the drying time by 36%. Hii et al. (2012) experimented to investigate the performance of a heat pump dryer for cocoa beans drying at drying temperatures of 28.2°C, 40.4°C, and 56°C. Minea (2012) experimentally analyzed the heat pump drying of the hardwood using the R-134a as a working refrigerant in temperature ranges from 39-54°C. the author found the values of COP as 3 and SMER from 2.1 to 2.5kg/kWh. Shi et al. (2013) experimented to investigate the drying kinetics and characteristics of the heat pump drying of the yacon slices at different drying temperature ranges from 5-45°C. Yang et al. (2013) investigated and proposed a method to control the temperature in the closed-loop drying of the heat pump that can be used as a heating and refrigeration cycle.

Erbay and Hepbasli (2013) carried out the advanced exergy analysis of the heat pump dryer using the R-407C refrigerant for the plum drying at drying temperatures of 45°C, 50°C, 55°C, and air velocity of 1.5m/s to investigate the exergy destruction and the inefficiencies in the subcomponents. The author observed that the advanced exergy value increases from 65.94 to 91.95% with the increase in drying air temperature from 45 to 55°C and the inefficiencies in the compressor and condenser are due to internal operating conditions. Ganjehsarabi et al. (2014) experimentally carried out the exergoeconomic analysis of the heat pump tumbler dryer (using R-134a refrigerant) at a drying temperature of the 68°C. The COP values and the SMER were estimated as 2.28 and 1.08kg/kWh respectively. The author concluded that the condenser is having the highest exergy inefficiency (79%) and exergy destruction cost rate. Bellomare and Minetto (2015) studied the hydrocarbons refrigerant in the heat pump dryer such as R-290 and R-441A instead of R-407C and the author concluded the increase in energy consumption with the new refrigerants. Aktas et al. (2015) experimentally investigated the performance of the heat pump dryer (using R-134a refrigerant) for the bay leaves drying and optimized the parameters using the artificial neural network method at drying temperatures of 40°C, 45°C, and 50°C. The COP of the whole system and the energy utilization ratio varies from 2.4-3.2 and 0.22-0.75. Gao et al. (2016) studied the effect of the various drying parameters on the volatile compound in silver carp drying. The experiment was performed for 5-35°C and concluded that the volatile compound content increases with an increase in velocity and by-pass air ratio. Bansal et al. (2016) studied the air leakage in heat pump clothes dryers to minimize the energy consumption using the new methods suggested by ASTM. Zhu et al. (2016) experimentally investigated the intermittent heat pump drying (using R-22 refrigerant) of the green soybean and analyzed the product kinetics at a drying temperature of 33°C. It was concluded that the intermittent drying and the intermittency give the best result as compared to continuous drying. Chapchaimoh et al. (2016) experimented to investigate the performance analysis of the heat pump dryer (using R-22 refrigerant) for the ginger drying at 50°C drying temperature using nitrogen as a working drying medium. For ginger, the SMER was 0.06 kg/MJ for air medium and 0.07kg/MJ for nitrogen and SEC was 16.67MJ/kg for air and 14.29MJ/kg for nitrogen. Jayaprakash et al. (2016) studied the effect of heat pump drying on the flavor of the tomato and compared the flavor of dried tomato with the fresh and freeze tomato. Yang et al. (2016) proposed a strategy to control the superheat and the drying air temperature simultaneously using a PID controller. Liu et al. (2017) designed and developed a heat pump drying room for the Lentinula edodes and concluded the remarkable energy saving with a better quality of the product as compared to the hot air drying method. Li et al. (2017) studied the effect of ultrasound-assisted osmotic dehydration as pre-treatment for the heat pump drying of the tilapia fillets. Gan et al. (2017) experimentally studied the heat pump dryer (using R-22 refrigerant) for the intermittent drying of the Malaysian edible bird's nest at a drying temperature of 28.6-40.6°C. It was estimated that intermittent drying at 28.6°C of temperature, 26.7% relative humidity, and 0.2 intermittency reduces the drying time by 84.2% with good color quality and energy efficiency. Aktas et al. (2017) experimentally investigated the drying kinetics and the performance analysis of the heat pump dryer (using R-410A refrigerant) for mint leaves drying in a new cylindrical drying chamber at a drying temperature of 30°C and air velocity of 2, 2.5 and 3.0m/s. The COP of the heat pump and the heat gain in the heat recovery unit were 3.94 and 4.56kWh respectively. Coskun et al. (2017) investigated the drying kinetics of the tomato slices in the closed-loop heat pump dryer at a different drying temperature of 30-45°C. The author concluded the COP and the SMER of HPD as 2.71 and 0.324kg/kWh respectively. Shen et al. (2018) developed and investigated the dual-mode heat pump dryer which can be operated as a single-stage and cascade stage heat pump dryer system depending on the requirement of drying temperature. The maximum temperature that can be obtained was 70°C in cascade mode. Taseri et al. (2018) experimented to study the drying kinetics and the product quality of the grape pomace drying with a heat pump dryer (using R-410A refrigerant) at 45°C of drying temperature. Patel et al. (2018) have studied the performance of the thermoelectric heat pump dryer for clothes drying. Atalay (2019) carried out the comparative analysis of the solar dryer and the heat pump dryer for the drying of the tomato using the exergy and exergoeconomic methodology. Dikmen et al. (2019) experimented to investigate the performance of the vacuum heat pump dryer for the drying of the medical plants such as sweet basil, parsley, and dill leaves at the vacuum pressure of 0.6 bar and the drying temperatures of 36 and 46°C. Gataric et al. (2019) studied the heat pump tumble dryer for textile drying and analyzed the effect of the various parameters such as fan speed, drum speed, and weight and initial moisture content of the material. Mohammadi et al. (2019) studied the performance and kinetics of the heat pump dryer (using R-134a refrigerant) for kiwi fruits drying at drying temperatures of 45°C, 55°C, and 65°C. The authors calculated the convective mass transfer coefficient, SMER, SEC, and drying efficiency at 65°C and 100% air recirculation as 4.12-8.55 E^{-7} m/s, 0.11-0.15kg/kWh, 1.08-1.49 kWh/kg and 9.84-12.15 % respectively. Tajudin et al. (2019) experimented to investigate the kinetics analysis of the Roselle calyx with a heat pump dryer and compared the result with a solar dryer at a temperature of 40°C, 50°C, and 60°C. Duan et al. (2019) developed a cascade heat pump dryer for the drying of the hawthorn cake to investigate the performance of the system in the temperature range between 66-68°C and compared the result with the hot air dryer. Kumar et al. (2020) experimented to study the performance of the heat pump dryer for the drying of the Moringa leaves under the vacuum pressure inside the drying chamber at the velocity of 1.1 and 1.4m/s. Onyocha et al. (2020) designed and developed a heat pump dryer using R-134 refrigerant for the fabrics drying at a temperature of 49°C. Tunckal and Doymaz (2020) studied the drying of the banana chips in the closed-loop heat pump drying system at different drying air temperatures and investigated the performance of the system and kinetics of the product.

Table: 2.2. Literature review on experimental analysis of simple heat pump dryer

Author	Drying product	Refrigerant	Drying temperature	Findings
Klocker et al. (2001)	Clothes	CO_2	50°C	MER = 5kg/h, SMER = 2.05kg/kWh, SEC = 0.49kWh/kg with 65% energy saving.
Ogura et al. (2002)	……..	………	130°C	Drying air temperature improved with enlarging the heat exchanger.
Oktay (2003)	Wet wool	R-22	50°C	The COP_{WS} = 2 - 3.5, SMER = 1.5 - 2.8kg/kWh which depends on the recirculation air ratio.

Oktay and Hepbasli (2003)	Wet wool	R-22	60°C	SMER= from 0.65 - 1.75 kg/kWh and the heating coefficient of performance ranged from 2.47 to 3.95.
Ameen and Bari (2004)	Clothes	………..	40°C	The drying time (2h) and the drying rate (0.424 kg/h) were much better.
Queiroz et al. (2004)	Tomato	R-22	40°C, 45°C, 50°C	Heat pump effective COP between 2.56 to 2.68.
Adapa and Schoenau (2005)	Crops, herbs	R-134a	30-35°C	The re-circulating air in HPD made it 22% more energy efficient with 65% reduced drying time.
Chua and Chou (2005)	…….	R-22	………	Recovered 35 % more heat with the two-stage evaporator, with sub-cooler SMER and COP improved.
Fatouh et al. (2006)	Herbs	R-134a	55°C	Lower size herb requires lower specific energy consumption and dying time.
Hawlader et al. (2006)	Apple, guava, potato	……..	45°C	Modified atmosphere HPD having better food quality.
Hawlader et al. (2006)	Ginger	…….	40°C	Better product quality and lower drying time

				with nitrogen and CO_2 medium.
Ceylan et al. (2007)	Poplar, pine timber	R-404A	40°C	The drying time, COP, and SMER for the poplar and pine were 70h, 1.86, 0.243 kg/kWh, and 50h, 1.87, 0.188kg/kWh respectively
Alves et al. (2008)	Protein	……….	…………	The two-stage drying is the more efficient and environmentally friendly method.
Shi et al. (2008)	Horse mackerel	R-134a	20-30°C	SMER was maximum for the bypass air ratio of 0.6-0.8.
Pal et al. (2008)	Green sweet pepper	……….	30°C, 35°C, 40°C, 45°C	HPD at 40°C requires less drying time with a better drying rate and SMER as compared to the hot air drying at 45°C.
Phoungchandang et al. (2008)	Kaffir lime leaf	…….	40°C, 50°C, 60°C	Heat pump drying reduced drying time.
Phoungchandang et al. (2009)	Ginger	…………	40-60°C	Heat pump drying at 40°C showed the best color and quality of the ginger.
Erbay and Icie (2009)	Olive leaves	R-407C	45-55°C	The optimum drying air temperature and velocity were 53.43°C and 0.64m/s.

Artnaseaw et al. (2010)	Red chili	R-22	50-65°C	Midilli agrees with the best model for the red chili thin layer model.
Jinjiang and Yaosen (2010)	Paddy	……..	42-46°C	The reduction in total drying time, cost and energy consumption were 88%, 64%, and 58%.
Chin and Law (2010)	Ganoderma tsugae	…………	40.6°C	Heat pump drying has better product quality.
Hepbasli et al. (2010)	Plum slice	R-407C	45-55°C	The exergy destruction rates to capital cost ratio varied between 1.668 and 2.063W/$.
Wang et al. (2011)	Hawthorn cake	R-22	40-70°C	The drying rate was higher for HPD at the same drying air temperature.
Phoungchandang and Saentaweesuk (2011)	Ginger	………	40-60°C	The HPD with two-stage drying could reduce the drying time at 40 ◦C by 59.32%.
Castell-Palou and Simal (2011)	Cheese	……….	0°C, 4°C, 8°C, 12°C	The mean relative error (MRE = 2.9%).
Mancini et al. (2011)	Clothes	CO_2,R-134a	30-50°C	A CO_2 heat pump dryer can be recommended for a household dryer.
Gungor et al. (2012)	Medical plants	………..	45°C	The performance of the drying process

				increases at low ambient temperature.
Senadeera et al. (2012)	Bovine intestine	R-134a	-5-25°C	The investigation showed that the drying kinetics were mostly affected by temperature.
Ong et al. (2012)	Salak fruit	………	26-90°C	The heat pump intermittent drying reduced the drying time by 36%.
Hii et al. (2012)	Cocoa beans	**………**	28-56°C	Percent retention of cocoa polyphenols ranged from 44% to 73% as compared to the freeze-dried sample.
Minea (2012)	Wood	R-134a	39-54°C	The COP as 3 and SMER from 2.1 to 2.5kg/kWh.
Shi et al. (2013)	Yacon	………	5-45°C	The effective diffusivity coefficients increased with increasing drying temperature.
Yang et al. (2013)	……	…………	30, 35, 38°C	The temperature fluctuations were reduced when using parallel conversion control.
Erbay and Hepbasli (2013)	Plums	R-407C	45-55°C	Inefficiencies in the compressor and condenser are due to

				internal operating conditions.
Ganjehsarabi et al. (2014)	Clothes	R-134a	68°C	The COP values and the SMER were estimated as 2.28 and 1.08kg/kWh.
Bellomare and Minetto (2015)	Clothes	R-290, R-441A, R-407C	………	Experimental data showed that R441A had very low compression efficiency.
Aktas et al. (2015)	Bay leaves	R-134a	40°C, 45°C, 50°C	The COP of the whole system and the energy utilization ratio varies from 2.4-3.2 and 0.22-0.75.
Gao et al. (2016)	Silver carp	………	5°C, 20°C, 35°C	optimum temperature, velocity, and bypass ratio for drying were 20°C, 1.65m/s, and 0.6 respectively.
Bansal et al. (2016)	Clothes	………..	………	Conclude the ASTM as an effective method to determine the air leakage in drying system.
Zhu et al. (2016)	Green soybean	R-22	33°C	Intermittent drying gives the best result.
Chapchaimoh et al. (2016)	Ginger	R-22	50°C	The SMER was 0.06kg/MJ for air medium and 0.07 kg/MJ for nitrogen.

Jayaprakash et al. (2016)	Tomato	……..	40°C	The volatile and sensory profiles of heat pump dried tomato were better than freeze-dried tomato, with good content of fresh aroma.
Yang et al. (2016)	…………	………..	28-31.2°C	The overshoot of drying temperature was less than 0.3°C and the superheat is controlled at 5±0.5°C during drying.
Liu et al. (2017)	Lentinula edodes	……..	33°C	The hump pump drying room is reasonable and reliable; the energy-saving and emission reduction effect is remarkable.
Li et al. (2017)	Tilapia fillets	……..	45°C	The ultrasound-assisted osmosis pre-treatment can improve the quality of the product.
Gan et al. (2017)	Bird's nest	R-22	28.6-40.6°C	Intermittent drying reduces the drying time by 84.2% with good color quality and energy efficiency.

Aktas et al. (2017)	Mint leaves	R-410A	30°C	COP of the heat pump and the heat gain in the heat recovery unit were 3.94 and 4.56 kWh respectively.
Coskun et al. (2017)	Tomato slices	…….	35°C, 40°C, 45°C	The SMER and COP of HPD were obtained as 0.324kg/kWh and 2.71.
Shen et al. (2018)	…….	R-22, R-134a	70°C	The COP of single-stage was higher.
Taseri et al. (2018)	Grape pomace	R-410A	45°C	The heat pump dryer has 51% less energy consumption compared to the convective dryer.
Patel et al. (2018)	Clothes	…………	35-40°C	A faster drying time of 96 min was observed as compared to the 159min in an electric heater.
Atalay (2019)	Tomato	R-404A	50-60°C	The exergoeconomic factor values were determined as 0.514 for solar dryer, and 0.045 for HPD.
Dikmen et al. (2019)	Sweet basil, parsley, dill leaves	………	36°C, 46°C	Chi-square values were found to be varying from $6.98E^{-07}$ to $1.2E^{-06}$ for sweet basil samples.

Gataric et al. (2019)	Textiles	………	………	This resulted in higher energy efficiency with high load, high drum speed, and low fan speed.
Mohammadi et al. (2019)	Kiwi fruits	R-134a	45°C, 55°C, 65°C	The SMER was found as 0.11-0.15kg/kWh.
Tajudin et al. (2019)	Roselle calyx	……..	40, 50, 60°C	Better product quality for the heat pump as compared to solar drying.
Duan et al. (2019)	Hawthorn cake	R-134a	66-68°C	The SMER was found to be 0.93kg/kWh.
Kumar et al. (2020)	Moringa leaves	R-134a	50°C	MER increases with a decrease in pressure and increase in temperature and velocity of drying air.
Onyocha et al. (2020)	Fabrics	R-134a	49°C	The COP of the system was estimated as 10.09.
Tunckal and Doymaz (2020)	Banana	……	37°C, 40°C, 43°C	The SMER and COP were obtained as 0.212kg/kWh and 3.059.

2.3. Theoretical studies on hybrid source heat pump dryer

The hybrid source heat pump dryer uses an extra source of energy assisted with the heat pump cycle to increase the performance of the drying system. Most of the researchers are working on the nonconventional source of energy to assist the heat pump dryer because of the availability at very low cost or free of cost. Many researchers have worked theoretically on the solar-assisted, ground source-assisted, and infrared-assisted heat pump dryer using the mathematical modeling of the system.

Hawlader and Jahangeer (2006) developed a simulation program for the solar-assisted heat pump drying system and obtained the COP of 7.5 at 1800 rpm of compressor and SMER of 0.65 at 1200rpm for the 20kg drying of the green beans. Slim et al. (2008) developed a mathematical model to study the performance of the solar heat pump (using R-407C refrigerant) sludge drying system. For the mild climatic period, the COP of the heat pump was 5.2 and for the winter season, it was found to be 4.9. Kuan et al. (2019) proposed a numerical model to study the thermal performance of the solar-assisted heat pump dryer (using R-134a refrigerant) and compared the result with heat pump and solar dryer in different climatic conditions for the banana drying. The drying temperature ranges from 20-50°C for all types of systems. The author estimated the drying time for the heat pump dryer and solar dryer as 21h and 35h and solar-assisted heat pump dryer, the COP and SMER were 2.72 and 0.6kg/kWh. Ismaeel and Yumrutas (2020) developed a simulation model for the performance analysis of the solar-assisted heat pump dryer with energy storage and heat recovery using a flat plate solar collector. At a drying temperature of 60°C for wheat drying, the values of COP and SMER were 5.55 and 9.25kg/kWh with an airflow rate of 100kg/h.

Table: 2.3. Literature review on theoretical analysis of hybrid source HPD

Author	Drying product	Source of energy	Drying temperature	Findings
Hawlader and Jahangeer (2006)	Green beans	Solar energy	50°C	The COP of the system is 7.5 at 1800 rpm of compressor and SMER as 0.65 at 1200 rpm for the 20 kg.

Slim et al. (2008)	……….	Solar energy	50°C	For the mild climatic period, the COP of the heat pump was 5.2 and for the winter season, it was found to be 4.9.
Kuan et al. (2019)	Banana	Solar energy	20-50°C	The COP and SMER were 2.72 and 0.6kg/kWh.
Ismaeel and Yumrutas (2020)	Wheat	Solar energy	60°C	The values of COP and SMER were 5.55 and 9.25kg/kWh with an airflow rate of 100kg/h.

2.4. Experimental studies on hybrid source heat pump dryer

Many open experimental works of literature are available on the hybrid source heat pump dryer using solar energy, ground source energy, infrared energy, and other sources for the drying of the different products.

Best et al. (1996) experimented to investigate the performance analysis of the solar-assisted heat pump dryer for rice drying at an average drying temperature of 30.8°C. The estimated values of COP and SMER were 5.3 and 3.5kg/kWh respectively. Hawlader et al. (2003) designed and developed the solar-assisted heat pump dryer with water heating for the drying of the food grains at the drying. The experimental and simulation value of COP were found as 5.0 and 7.0 respectively with solar fraction values of 0.65 and 0.61 for simulation and experimental. Hawlader and Jahangeer (2006) investigated the performance of the solar-assisted heat pump dryer using the experimental analysis with the simulation model for the drying of the green beans at a drying temperature of 45-55°C. The COP, SMER, and the solar fractions were 7.0, 0.65kg/kWh, and 0.81 respectively. The authors concluded that both COP and SMER decrease with an increase in compressor speed. Xie et al. (2006) studied the solar-assisted heat pump dryer with energy storage for the drying of the agricultural products at different temperatures of 40°C, 50°C, and 60°C respectively. COP of the solar-assisted heat pump drying system was 5.369, while it was 3.411 without solar assisted. Kuzgunkaya and hepbasli (2007) carried out the exergy analysis of the ground source-assisted heat pump dryer for laurel leaves drying and investigated the effect of the drying temperature on exergy loss and exergy efficiency. Colak et al. (2008) experimentally investigated the ground source-assisted heat pump dryer for the drying of the mint leaves in the temperature range of 40-50°C. Aktas et al. (2009) carried out the performance and the kinetic analysis of the solar dryer and the heat pump dryer for the apple slice drying at a temperature of 40°C for the heat pump and 16-30°C for the solar dryer. The effective moisture diffusivity for heat pump and solar dryer were $2.36E^{-8}$ and $1.03E^{-8}$ respectively with a drying time of 3.5h for heat pump drying. Fadhel et al. (2010) experimentally investigated the performance of the solar-assisted chemical heat pump dryer and also a simulation model was developed and compared the predicted results with the experimental data for the drying of the lemongrass at 55°C temperature and 30% of relative humidity. The solar fraction and the COP of the system were found as 0.713 and 2. Deng et al. (2011) studied the far-infrared assisted heat pump dryer and investigated the drying kinetics and properties of squid fillets at different combinations of the heat pump and infrared radiation. Gungor et al. (2011) analyzed the exergy performance of the gas engine-driven heat pump (using R-407C refrigerant) dryer with the utilization of the exhaust heat for heating the drying air for the drying of the medicinal and aromatic plants at a drying temperature of 45°C and air velocity of 1.0 m/s. It was concluded that 60% of exergy accounts for the gas engine, expansion valve, and drying ducts, and the overall exergy efficiency ranges from 48.24 to 51.28 %. Li et al. (2011) conducted the numerical and the experimental analysis of the solar-assisted heat pump dryer for the drying of the corn grain in house storage at drying temperature between 20-40°C. The dying rate was increased with the increase of drying air by 8.9°C with solar-assisted heat pump drying. Mortezapour et al. (2012) carried out the experimental analysis of the hybrid solar-assisted photovoltaic heat pump dryer (using R-134a refrigerant) for the saffron drying at drying temperatures of 40°C, 50°C, and 60°C. It was concluded that the energy consumption decreases by 33% with solar-assisted HPD and the maximum values of drying efficiency and SMER were 72% and 1.16kg/kWh at 60°C of drying air.

Rahman et al. (2013) experimentally and numerically carried out the economic analysis of the solar-assisted heat pump dryer (using R-134a refrigerant) at a drying temperature of 50°C for the drying of food grains. Based on economic analysis, the payback period was found to be more than 4 years. Sevik et al. (2013) investigated the performance analysis of the solar-assisted heat pump dryer which can be used as only solar dryer and heat pump dryer as well as both together. The author dried the mushroom at drying temperatures of 45 and 55°C and found the SMER varies from 0.26 to 0.92kg/kWh. Zielinska et al. (2013) studied the microwave-assisted fluidized bed heat pump drying of the green peas and compared the result with the fluidized bed heat pump freeze-drying and fluidized bed heat pump convective hot air drying. Erbay and Hepbasli (2014) experimented and determined the advanced exergy analysis of the ground source heat pump dryer (using R-22 refrigerant) for food drying at a drying temperature of 45°C and relative humidity of 16-19%. The conventional and advanced exergy efficiency values were found as 77.05% and 93.5%. Sevik (2014) experimented to analyze the solar-assisted heat pump system for the drying of the tomato, strawberry, mint, and parsley at a drying temperature of 50°C. The specific moisture extraction rate was between 0.03 to 0.46kg/kWh. Mohanraj (2014) investigated the performance of the solar hybrid heat pump (using R-22 refrigerant) dryer for the copra drying in a hot and humid environment at a drying air temperature of 41-48°C. The average value of COP and SMER were found as 2.54 and 0.79kg/kWh with higher quality as compared to the other drying methods. Wang et al. (2016) studied the infrared assisted heat pump dryer to investigate the moisture distribution and the kinetics of the squid fillets with infrared radiation at 100, 500, and 800 W. All the experiments were conducted at the drying temperature and air velocity of 40°C and 2m/s. The author concluded the significant effect of infrared radiation on the moisture distribution and rate of water sorption. Yahya et al. (2016) investigated the thermal performance of the solar dryer and the solar-assisted heat pump dryer for the drying of the cassava roots. The drying temperature was 40°C for the solar dryer and 45°C for the solar-assisted heat pump dryer at an air mass flow rate of 0.124kg/s and takes the drying time 13 h and 9 for SD and SAHPD. The average COP of the heat pump system was 3.38 with SMER of 0.38kg/kWh for solar dryer and 0.47kg/kWh for solar assisted HPD. Aktas et al. (2016) developed a heat pump dryer (using R-134a refrigerant) and the infrared and investigated the performance of both dryers for the drying of the stale bread at drying temperatures of 40°C, 45°C, and 50°C. The COP of the whole system was calculated as 3.7 and drying efficiency was 39% and 25% for the infrared dryer and heat pump dryer. Qiu et al. (2016) developed a solar-assisted heat pump drying system with heat recovery and thermal storage of the solar energy which can be operated as either a solar dryer, heat pump dryer, or solar-assisted heat pump dryer for the radish, pepper, and mushroom drying. The drying temperature ranged from 30°C to 50°C and calculate the COP varies from 3.21 to 3.49. The author calculated the payback period for the radish, pepper, and mushroom as 6 years, 4 years, and 2 years respectively. Ceylan and Gurel (2016) studied the thermal performance of the fluidized bed solar assisted heat pump drying system for the mint leaves drying using energy and exergy methodology at drying temperature of 45°C for the solar system and 50°C for the HPD system. The author calculated the energy and exergy efficiency of the

SAHPD system as 50% and 26% respectively with the COP of the HP system as 5.0. Tham et al. (2017) studied the performance of the solar greenhouse-assisted heat pump dryer for the drying of the Java tea and the Sabah snake grass.

Erbay and Hepbasli (2017) carried out the exergoeconomic investigation of the ground source heat pump (using R-22 refrigerant) dryer at a drying temperature of 40°C and relative humidity of 16-19%. From the exergoeconomic analysis, the author concluded the compressor is the most important component of the system with a total cost rate of 1.347$/h and exergoeconomic factor of 0.029. Aktas et al. (2017) conducted the experimental performance analysis of the hybrid source of drying system that combines the advantages of the infrared radiation and the heat pump system (using R-134a refrigerant) at a drying temperature of 45-50°C and air velocity of 0.5m/s for the grated carrot drying. The energy efficiency, COP, and exergy efficiency varied from 5.3-50%, 2.11-2.96, and 31.6-66.8% respectively.

Table: 2.4. Literature review on experimental analysis of hybrid source HPD

Author	Drying product	Source of energy	Drying temperature	Findings
Best et al. (1996)	Rice	Solar energy	30.8°C	The estimated values of COP and SMER were 5.3 and 3.5kg/kWh respectively.
Hawlader et al. (2003)	Foodgrains	Solar energy	…………	The experimental and simulation value of COP and solar fraction were found as 5.0 and 7.0 and 0.65 and 0.61.
Hawlader et al. (2006)	Green beans	Solar energy	45-55°C	The COP, SMER, and the solar fractions were 7.0,

				0.65kg/kWh, and 0.81 respectively.
Xie et al. (2006)	Agriculture product	Solar energy	40, 50, 60°C	The COP of the SAHP drying system is 5.369, while it is 3.411 without solar energy inputs.
Kuzgunkaya and Hepbasli (2007)	Laurel leaves	Ground source energy	40-50°C	The exergy efficiencies of the dryer increase with rising the drying air temperature.
Colak et al. (2008)	Mint leaves	Solar energy	40-50°C	The exergy efficiency was maximum at the temperature of 50°C and a drying air mass flow rate of 0.05kg/s.
Aktas et al. (2009)	Apple	Solar energy	40°C, 16-30°C	The effective moisture diffusivity for the heat pump and solar dryer were $2.36E^{-8}$ and $1.03E^{-8}$.
Fadhel et al. (2010)	Lemongrass	Solar energy	55°C	The solar fraction and the COP of the system were found as 0.713 and 2.
Deng et al. (2011)	Squid fillets	Infrared energy	50°C	HP dried squids had higher equilibrium moisture contents followed by HP + 5FIR and HP + 20FIR.
Gungor et al. (2011)	Medicinal, aromatic plants	Gas engine	45°C	The overall exergy efficiency ranges from 48.24 to 51.28%.
Li et al. (2011)	Corn grain	Solar energy	20-40°C	The dying rate was increased with the increase of drying air by 8.9°C with

				solar-assisted heat pump drying.
Mortezapour et al. (2012)	Saffron	Solar energy	40°C, 50°C, 60°C	The maximum values of drying efficiency and SMER were 72% and 1.16 kg/kWh at 60°C of drying air.
Rahman et al. (2013)	Foodgrains	Solar energy	50°C	The payback period was found to be more than 4 years.
Sevik et al. (2013)	Mushroom	Solar energy	45-55°C	Moisture extraction rate (SMER) values were found to vary between 0.26 and 0.92kg/kW h.
Zielinska et al. (2013)	Green peas	Microwave energy	……….	The hardness of the product increases with the microwave vacuum assisted.
Erbay and Hepbasli (2014)	Foodgrain	Solar energy	45°C	The conventional and advanced exergy efficiency values were found as 77.05% and 93.5%.
Sevik (2014)	tomato, strawberry, mint, parsley	Solar energy	50°C	The specific moisture extraction rate was between 0.03 to 0.46kg/kWh.
Mohanraj (2014)	Copra	Ground source energy	41-48°C	The average value of COP and SMER were found as 2.54 and 0.79kg/kWh.
Wang et al. (2016)	Squid fillets	Infrared energy	40°C	There was a significant effect of infrared radiation on the moisture

				distribution and rate of water sorption.
Yahya et al. (2016)	Cassava	Solar energy	40°C, 45°C	The SMER of 0.38kg/kWh for solar dryer and 0.47kg/kWh for solar assisted HPD.
Aktas et al. (2016)	Stale bread	Infrared energy	40°C, 45°C, 50°C	The COP of the whole system was calculated as 3.7.
Qiu et al. (2016)	Radish, pepper mushroom	Solar energy	30°C, 50°C	The payback period for the radish, pepper, and mushroom were 6 years, 4 years, and 2 years respectively.
Ceylan and Gurel (2016)	Mint leaves	Solar energy	40°C- 50°C	The energy and exergy efficiency of the SAHPD system as 50% and 26%.
Tham et al. (2017)	Java tea, Sabah snake grass	Solar energy	45°C	Applying the heat pump with a solar greenhouse improves the drying rate.
Erbay and Hepbasli (2017)	………..	Ground source energy	40°C	The compressor has a total cost rate of 1.347$/h and exergoeconomic factor of 0.029.
Aktas et al. (2017)	Carrot	Infrared energy	45°C, 50°C	The energy efficiency, COP, and exergy efficiency varied from 5.3-50%, 2.11-2.96, and 31.6-66.8% respectively.
Yahya et al. (2017)	Rice	Solar energy	80.6°C	The average SMER was 0.24kg/kWh with a payback period of 1.6 years.

EI khadraoui et al. (2017)	…….	Solar dryer	68°C	The energy efficiency of the solar energy accumulator reached 33.9%.
Rabha et al. (2017)	Ghost chili paper and ginger	Solar dryer	42-61°C	The SEC of the ghost chili and the ginger were 18.72kWh/kg and 8.82kWh/kg.
Lakshmi et al. (2019)	Stevia leaves	Solar dryer	50-59.5°C	The overall dryer efficiency and average exergy efficiency of the MFSCD were found as 33.5% and 59.1%, respectively.
Ekka et al. (2020)	Black ginger	Solar dryer	45-62°C	The estimated SECs for Case – 1 and Case – 2 were 1.0 kWh/kg and 0.56kWh/kg, respectively.
Ekka et al. (2020)	Red chili	Solar dryer	33-49.8°C	The FCMS dryer with PCM reduces the drying time by nearly 50%.
Khanlari et al. (2020)	Apricot	Solar air heater	45.9-50.8°C	The average efficiency of T-SAH was obtained as 45.56%, 53.29%, and 56.77% at 0.010, 0.013, and 0.015kg/s air flow rates, respectively.
Kumar et al. (2021)	…….	Solar dryer	……..	The value of energy and exergy efficiency of the SAH was obtained as 62.8% and 5.848%.

2.5. Research gap

After going through the literature survey, many literature gaps were found which are summarized below,

- No work is done on heat pump dryer using the low GWP refrigerants like R1234yf, R1234ze, and R152a (future refrigerants).
- No work is done on the solar-infrared-assisted heat pump dryer (SIAHPD)
- Little work is done on the economic and exergoeconomic analysis of the solar-assisted heat pump dryer
- No work is done on the heat pump dryer assisted with waste heat recovery from the exhaust of the IC engine
- No work is done on the intermittent drying of the solar-assisted heat pump dryer
- Little work is done on the heat pump dryer with air conditioning in a hot and humid environment

2.6. Objective of the present study

The research objectives of the present study are given below,

- Numerical analysis of heat pump dryer using low GWP refrigerants to compare their performances
- Design, development, and performance analyses of the dual-mode heat pump dryer
- Experimental study on solar-infrared assisted heat pump dryer and energy, exergy and economic analyses
- Experimental study on waste heat recovery assisted hybrid heat pump dryer and energy, exergy and economic analyses

- Experimental study on intermittent drying with solar-assisted heat pump dryer and energy, exergy, and economic analyses
- Experimental study on air conditioning integrated heat pump dryer and energy, exergy and economic analyses