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A Review on Solar Dryers to Evaluate the Performance and Drying Characteristics for Agricultural Products

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ABSTRACT

In this paper, an attempt has been made to review various research on drying agricultural products using solar radiation in a self-consistent means in the areas of performance analysis, energy, exergy analysis, experimental investigation, and optimization of solar dryers. Various simulation models to estimate the thermal performance and drying characteristics of diverse types of solar collectors have been presented. Some of the recent developments in solar drying systems are presented. Further, it is found that the dryers are classified as integral type, distributed type, and mixed mode. Previous research by different authors proved that the drying period of agricultural products decreased considerably by solar drying. It is concluded that this paper is very much supportive for the researchers, academicians, scientists, and policymakers in the area of solar dryers. Also, a standard test should be developed for solar drying systems.

Index-words: *Solar drying systems, Solar air heaters, Flat plate collectors, Tunnel dryers, Drying characteristics, Thermal performance, Hybrid solar dryers, Integral-type solar dryers, Greenhouse solar dryers.*

I. INTRODUCTION

Drying is solely the practice of moistness elimination from a product. It can be achieved by different means such as chemical desiccants, chemical decomposition, absorption in gases, mechanical methods, and thermal drying. Among these kinds of drying methods, thermal drying is normally employed for agricultural products drying such as crops, grains, vegetables, and fruits that involve the moisture content evaporation from the agricultural products by heat energy. Conventional drying methods are normally categorized as low and high temperature drying. In the last few decades, agricultural products are dried with the utilization of solar energy economically. Due to the increase in energy utilization and the cost of fossil fuels, the usage of solar dryers is increasing exponentially. Over the last 20 years, various studies were conducted in the areas of crops, grains, vegetables, and fruits drying using solar energy. Figure 1 illustrates the different types of solar dryers.

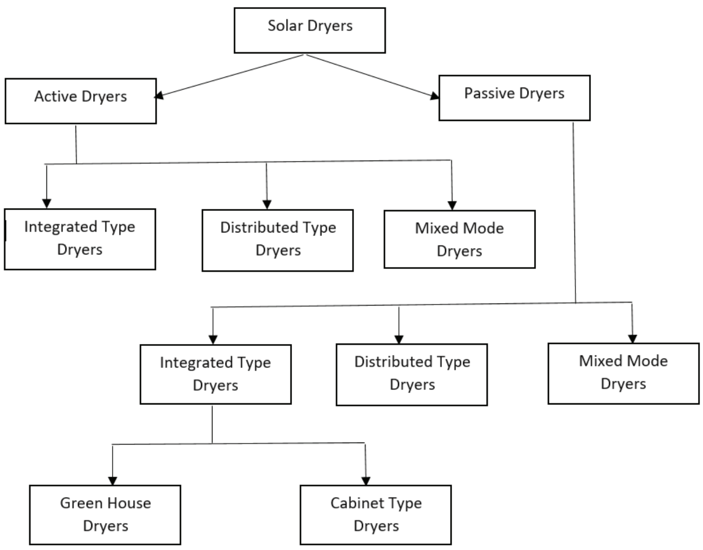

Fig. 1. Broad classification of solar dryers

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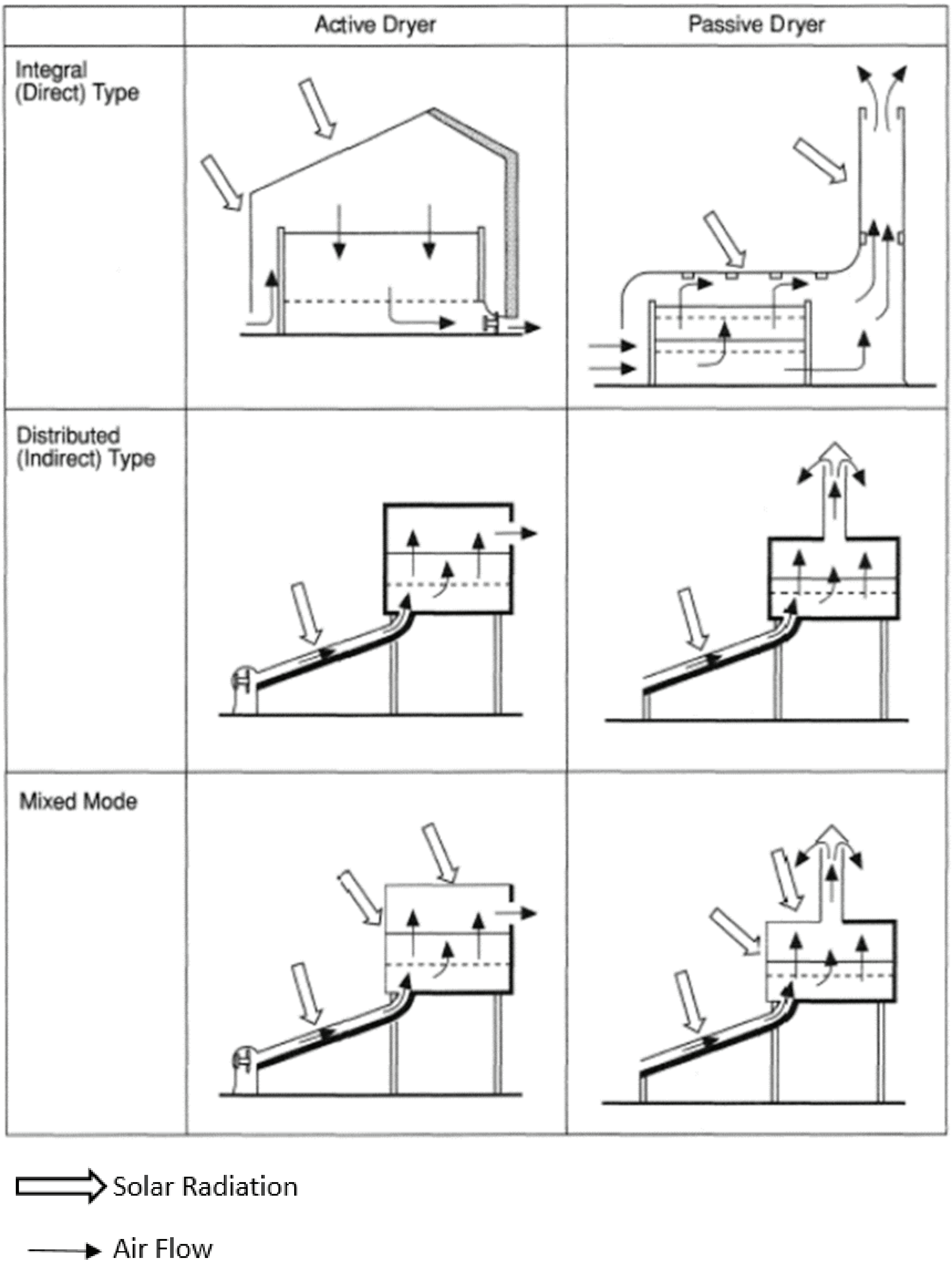

Fig. 2. Solar dryer types according to mode of working [1]

Figure 2 illustrates the diverse types of dryers according to the mode of working. In this paper, an effort has been made to highlight various research on solar drying using natural circulation systems, forced circulation systems, hybrid systems, integrated systems, direct drying units, distributed systems, indirect drying units, and mixed-mode units in a self-consistent means. The advances of these drying theories from earlier research are also presented. The various research papers related to thermal performance and drying characteristics of various solar dryers reveal that the drying time of crops, grains, vegetables, and fruits considerably reduced by drying in solar dryers without negotiating the product quality. From the results of the experiments conducted in various countries, it is identified that solar dryers are used very effectively for agricultural product drying.

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II. LITERATURE REVIEW

An extensive review has been conducted on the thermal performance and drying characteristics of solar dryers and is presented in this section. Alvin et al. (1985) studied the thermal characteristics of suspended-plate air heaters for grain drying and found that the efficiency is about 50 to 70 % [2]. Sharma et al. (1986) designed natural convective dryers for food preservation in rural regions and studied their performance and heat transfer characteristics [3]. Rolf and Gosta (1986) examined the use of diverse kinds of solar dryers and found that solar dryers were more economical when compared to using oil for heating and drying [4]. Ezeike (1986) developed and assessed a triple-pass flat plate solar collector having a length of 190 cm, a width of 122.5 cm, and a height of 23.5 cm and integrates two absorber plates separated by about 6 cm. The author found that the collector efficiency is around 73–81% [5]. Das and Yogender (1989) determined the efficiency of a drying system coupled with a chimney appropriate for use in villages [6]. Lawrence et al. (1990) performed an analysis on a crop dryer with energy storage for tapioca drying for the Papua New Guinea climatic conditions and the authors found that it is more economical [7]. Sanjay et al. (1990) formulated transient models and calculated the various drying parameters of a cabinet model dryer [8]. Adolfo and Vinod (1991) investigated the performance of an economical dryer for food preservation [9]. Sharma et al. (1992) examined the performance of an indirect multi-shelf dryer with plastic covered flat plate for fruits and vegetables drying with chemical pre-treatment and the authors found that the chemical pre-treatment increases the drying rate [10].

A practical evaluation was conducted by Bassey et al. (1994) in an air dryer fitted with a chimney and the performance was evaluated by varying the collector gap [11]. Sharma et al. (1995) investigated the performance of several types of dryers including the cabinet type dryer which is shown in the figure 3[12]. Cigdem et al. (1995) explored the thermal efficiencies of a dryer for the different mass flow rates of air and the authors found that the efficiency of the dryer enhanced when the airflow rate was high [13]. Ekechukwu and Norton (1997) investigated the thermal behaviour of a natural convective dryer fitted with a chimney [14]. In the year 1998, the authors analyzed the impact of climatic changes on the calculated efficiency of a natural convective dryer for the drying of crops in tropical regions [15]. David and Atsu (1998) evaluated the thermal behaviour of a cabinet-type dryer [16].

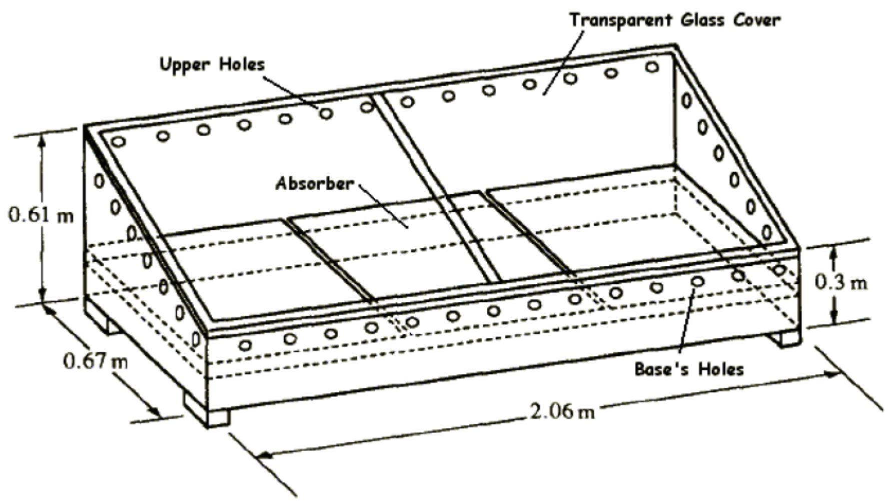

Fig. 3. Cabinet type solar dryer [12]

Miguel and Luis (1998) conducted a logical study to determine the performance of chamber-type forced convective greenhouse dryers and found that the double chamber dryer improves the efficiency by nearly 90% [17]. Ong (1999) studied the various kinds of dryers for usage in drying [18]. Oztekin et al. (1999) studied the various methods to dry the crops in Turkey using solar radiation [19]. Anwar and Tiwari (2001) determined the natural convective heat transfer coefficient in crop drying using solar radiation by considering the crops namely, Kabuli chana, green chillies, onion, potato, green peas, and cauliflower [20]. Najmur and Subodh (2006) determined the heat transfer coefficient during vegetable drying in a cabinet-type solar dryer [21]. Sreekumar et al. (2008) examined the performance of an indirect mode cabinet dryer for vegetables and fruits drying using solar radiation and the authors found that the drying rate increased [22]. Amer et al. (2010) fabricated and studied the performance of a hybrid dryer for banana drying [23]. James et al. (2012) estimated the performance of a concentrating panel dryer for fruit drying and found that the drying period decreased by 27 % [24].

Wisut et al. (2013) studied the desiccant bed dryer with a dehumidifier for chilli drying and the authors found that the dehydrating time of the dryer with a dehumidifier was 20.83 % quicker than a solar dryer without a dehumidification system [25]. Srivastava et al. (2014) determined the efficiency of an air heater with Lauric acid as a phase change medium to accumulate excess solar radiation [26]. Ahmad et al. (2015) analyzed an indirect forced convective drying unit for palm oil leaves drying and the authors concluded that the average exergy efficiency attained was 47 % [27]. Misha et al. (2015) studied the thermal characteristics of a solid desiccant dryer with low solar insolation for drying kenaf and the authors found that the drying time was reduced by 24% and the dryer attained an efficiency of 12% [28]. Dilip and Pratibha (2015) investigated the thermal efficiency of an indirect mode natural convective flat plate dryer for drying crops [29]. Misha et al. (2016) analyzed the behaviour of a solid desiccant drying system assisted by solar energy for drying crushed oil palm fronds and the authors found that the sensible and latent effectiveness of the dryer was 74% and 67%, correspondingly [30].

Miguel et al. (2017) developed a forced convective tunnel dryer for vegetable drying and the authors found that the solar air dryer efficiency was 60% [31]. Vivek et al. (2017) analyzed the drying characteristics of the dryer to preserve food by considering the environmental, design, and operational parameters [32]. Karunaraja et al. (2017) conducted experimental work on a convective tunnel drying unit with energy storage for crop drying and the authors found that the efficiency of the dryer was found to be 2-3% higher [33]. Kareem et al. (2017) studied the thermal characteristics of a forced convective multi-pass dryer incorporated with an energy storage medium for Roselle drying and the authors found that the drying efficiency of the unit was 36.22% [34]. Lakshmi et al. (2018) developed a mixed mode forced convective drying system with energy storage for sliced turmeric drying and the authors found that the overall efficiency of the dryer was 12% [35]. Majedul et al. (2019) piloted a study to determine the influence of cover design on the performance of a natural convection cabinet drying system for fruit and vegetable drying [36]. Younes et al. (2019) investigated the exergy efficiency by conducting a thermos-kinetic study of a natural convective and forced convective solar dryer for drying sardine heads [37]. Lopez-Vidana et al. (2020) investigated the thermal behaviour of a mixed flow passive drying system for tomato slices drying and the authors evaluated the overall dryer efficiency as 10.66% with mixed-mode and 8.80% with indirect solar drying mode [38]. Masnaji and Vinod conducted a review study on the performance of solar dryer considering dryer efficiencies and rate of moisture removal in the year 2021 [39]. Maedeh Leilayi (2023) conducted performance analysis of perforated drum type dryer for paddy drying by varying the rotational speed of the drum [40]. Goel et al. (2024) conducted a detailed review on dryers for domestic applications considering social and environmental factors [41].

A. *Energy and Exergy Analysis*

Energy and exergy analyses on various types of solar dryers are presented below. Sujata and Tiwari (2008) performed an exergy analysis to determine the functional effect of a photovoltaic/ thermal collector incorporated with a greenhouse and the authors found that the exergy efficiency is around 4% [42]. Abdullah and Aydin (2010) analyzed the influence of drying time and velocity of air at the inlet on the energy and exergy level of a forced convective dryer for mulberry drying. The authors found that there is a decrease in energy utilization ratio with the increase in air velocity, but the exergy efficiency increased [43]. Toyosi and Grace (2011) studied the influence of drying environments on the actual moisture diffusivity and energy necessities during the pumpkin drying for its preservation using solar energy [44]. Amel and Ahmed (2011) conducted an exergy study of an indirect type passive air heater for drying mint. The authors estimated the amount of solar energy received by the air heater from energy analysis and estimated the energy losses during the drying from exergy analysis [45]. Ahmad et al. (2014) conducted an energy and exergy analysis of a dryer for seaweed drying and investigated the drying kinetics [46]. Aymen et al. (2017) enumerated the thermal behaviour of an indirect forced convective drying unit with phase

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change material. The authors found that the energy and exergy efficiencies of the collector were 33.9% and 8.5%, correspondingly [47].

Ndukwu et al. (2017) conducted an exergy analysis of a natural convective dryer with energy storage for chili drying and determined the energy consumption and the exergy efficiency [48]. Mustafa et al. (2017) analyzed a hybrid drying unit to study the drying kinetic of grated carrots. The authors obtained that energy and exergy efficiencies were 50% and 66.8%, correspondingly [49]. Sumit and Tiwari (2017) set up a thermal model to evaluate the energy and exergy efficiencies of a mixed-mode greenhouse drying system. The authors concluded that the thermal and exergy efficiencies of the drying unit were 42.22% and 28.96%, respectively [50]. Karthikeyan and Murugavelh (2018) investigated the drying kinetics of turmeric in a forced convective tunnel type mixed-mode dryer. The authors found that the maximum energy utilization ratio of the dryer was 33.98% and the mean exergy efficiency of the dryer was 49.12% [51]. Yogendrasasidhar and Pydi (2018) analyzed the energy utilization ratio, and exergy study of fluidized bed dryer for drying millet and fenugreek seeds [52]. Prashant et al. (2018) conducted a heat transfer analysis of photovoltaic incorporated forced convective dryer for crop drying and estimated the exergy efficiency. The authors concluded that the energy and exergy efficiencies of the greenhouse dryer were found to be 16.8% and 21.4% with and without the solar collector, respectively [53]. Tunckal and Doymaz (2020) developed a mathematical model to evaluate the drying characteristics of banana [54]. Mugi and Chandramohan (2021) conducted that the exergy analysis of free and forced convective dryers and the exergy efficiency were estimated as was found to be 51.85% and 56.12, respectively [55]. Dutta et al. (2023) performed energy analysis of a dryer with heat energy storage unit and determined the drying efficiencies [56].

B. *Experimental Investigation*

Various research had been conducted to investigate the various drying parameters of crops drying using solar dryers and are presented below. Sharma et al. (1993) investigated the functional effect of an indirect mode dryer for crops and the authors recommended that the developed dryer was very economical for uses in farmhouses [57]. Vinod Kumar et al. (1995) studied the thermal behaviour of various models of natural and forced convection dryers for fruit and vegetable drying [58]. Schirmer et al. (1996) investigated the performance of tunnel type dryer and figure 4 shows the tunnel type dryer that the authors have used for performance investigation [59].

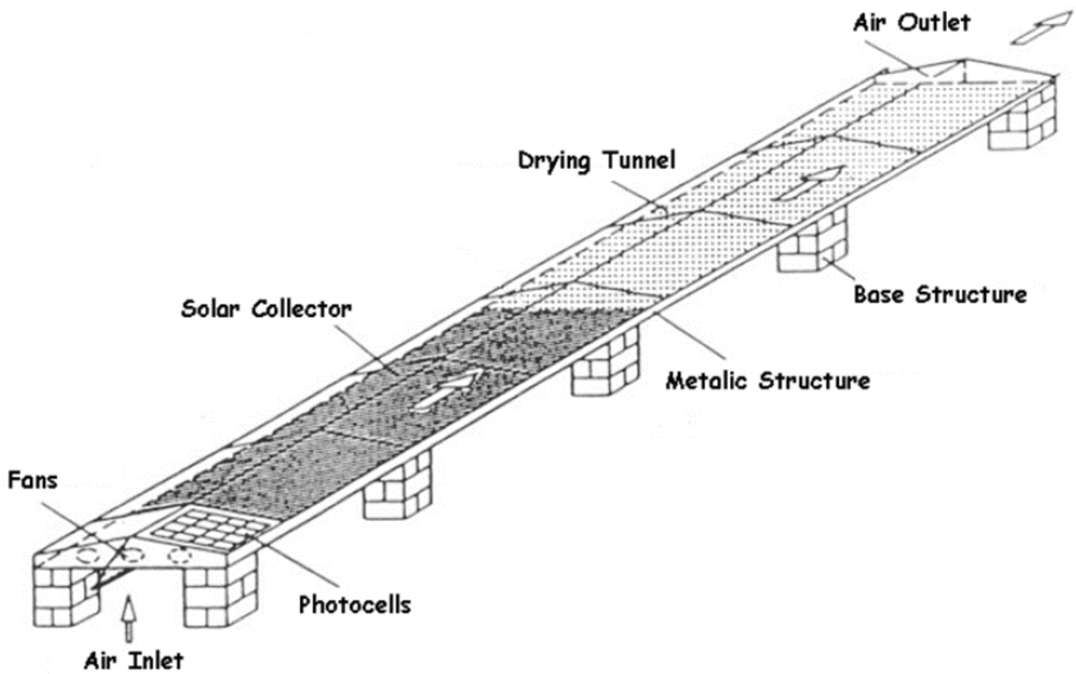

Fig. 4. Tunnel type solar dryer [59]

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Ekechukwu and Norton (1997) conducted an experimental study to determine the transient performance of integrated natural convective solar dryers for crop drying in tropical regions [60]. Hachemi et al. (1998) piloted an experimental study to evaluate the functional effect of forced convective air heaters for crop drying [61]. Esper and Muhlbauer (1998) investigated the performance of a food preservative dryer using solar radiation [62]. Anwar and Tiwari (2001) conducted a study on the forced convective dryer to determine the convection heat transfer coefficients for various crops [63]. El-Sebaii et al. (2002) determined the performance of an indirect model natural convective flat plate air heating unit using sand as the storage medium as shown in figure 5 and found the drying period decreased by 12 hours with

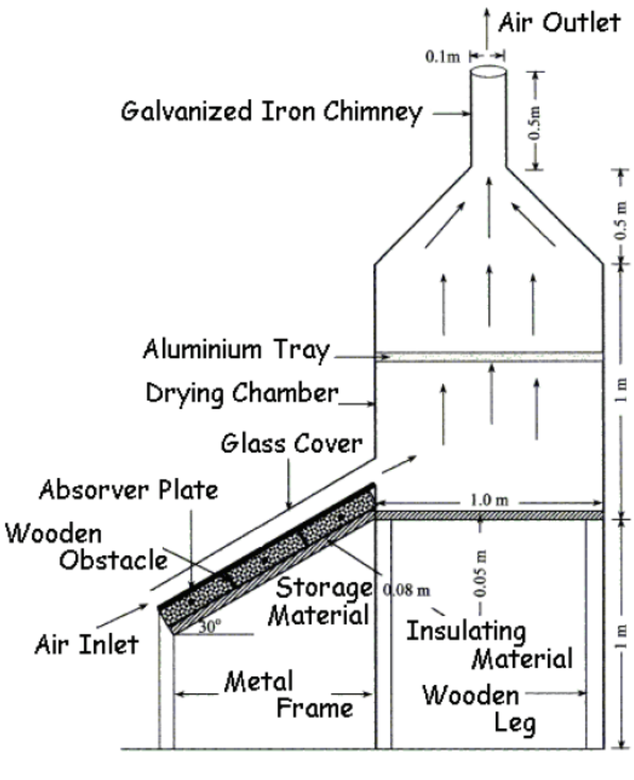

Fig. 5. Distributed type passive solar dryer [64]

the usage of the storage medium [64]. Janjai et al. (2008) conducted a study to determine the performance of a roof-integrated dryer for crop drying and the authors found that the drying period decreased significantly [65]. Afriyie et al. (2009) evaluated the functionality of a natural convection dryer with a chimney for crop drying [66]. Saadeddine et al. (2013) investigated the performance of an indirect type forced convective dryer for tomato drying in Algeria by considering the size of the tomato slices [67].

Samira et al. (2013) investigated the performance of an indirect hybrid dryer incorporated with photovoltaic panels which was constructed in Algeria for drying sliced potatoes and the authors found the drying time and quality of the product were improved while using the hybrid dryer [68]. El-Sebaii and Shalaby (2013) conducted a study to investigate the performance of an indirect forced convective corrugated plate dryer for mint and thymus drying and the authors found that the time taken to attain the final moisture content for mint and thymus was 5 hours and 34 hours, respectively [69]. David and Angel (2014) conducted a drying test for pineapple drying with a conventional dryer and a hybrid dryer. The authors found that the evaporation efficiencies are higher in the conventional drying process and that the drying time was found to be better in a hybrid solar dryer [70]. Seyfi (2014) conducted a study to determine the drying behaviour of a heat pump dryer for various agricultural drops drying under different weather conditions. The authors concluded that the thermal efficiency of the double-pass unit was between 16% and 79% [71]. Samira et al. (2014) conducted a valorization study of dates with three kinds of dryers such as direct natural convection, indirect convection, and indirect natural driers. The authors found that the quality of the dried dates was higher in drying with an indirect natural convection dryer [72]. Aymen et al. (2015) investigated the thermal behaviour of a forced convective mixed-mode dryer for grapes drying. The authors reached the conclusion that the drying time was improved by 17 hours [73]. Sekyere et al. (2016) analyzed the drying characteristics of a natural convective mixed-mode dryer incorporated with a heater in Ghana for crop drying and the authors evaluated the average moisture pickup efficiency for various climatic seasons [74].

Nabnean et al. (2016) analyzed the thermal characteristics of a dryer incorporated with an energy storage unit for dehydrated cherry tomatoes drying. The authors found that the drying time decreased and the efficiency was evaluated as in the range from 21% to 69% [75]. Roonak and Abdellah (2016) conducted a study of a heat pipe air heater incorporated with a heat recovery unit for the enhancement of performance and the authors found the dryer attained a temperature of 44.3 °C at the outlet. The authors also evaluated the exergy efficiency of the dryer and attained a maximum value of 11.7% [76]. Tadahmun and Hussain (2016) investigated the enhanced performance of a hybrid dryer incorporated with a heat recovery unit for red chilli drying. The authors reached the conclusion that the overall drying efficiency was 10.3% without a heat recovery unit and increased to 13% with a heat recovery unit [77]. Adnane et al. (2016) calculated the thermal performance of the different models of flat plate dryers experimentally for henna drying and the authors found that the drying time 75% reduced [78]. Fevzi et al. (2016) analyzed the drying parameters of a dryer experimentally and analytically for drying sweet basil and the authors found that the collector attained the maximum value of 63% [79]. Ehsan et al. (2017) examined the thermal behaviour of a forced convective mixed-mode drying system incorporated with heat storage for drying apricot. The authors found that the overall thermal and moisture pickup efficiencies were 11% and 10%, correspondingly [80]. Kareem et al. (2017) analyzed the characteristics of a multi-pass dryer for screw-pine leaf drying in Malaysia and the authors found that the collector attained a drying efficiency of 36.04% with a pickup efficiency of 66.95% [81]. Fterich et al. (2018) conducted a study on a forced convective mixed-mode dryer integrated with a photovoltaic/thermal heating unit for tomatoes drying and the authors found that the drying temperature and the dried product quality improved [82].

Chandrasekar et al. (2018) enhanced the drying rate of a dryer by incorporating the condenser of a split air conditioning unit for grapes drying in India. The authors found that the drying time reduced by 16.7% and the dryer efficiency increased to 13% [83]. Abdelhamid et al. (2018) conducted a study on the drying of Tunisian phosphate in various kinds of dryers and the authors found that the parabolic dish collector performance became higher [84]. Shamsi et al. (2019) determined the fuel consumption and drying behaviour of lemon leaves in a continuous flow dryer incorporated with a pre-heating unit [85]. Saeed et al. (2019) conducted an energy analysis of a fluidized-bed dryer integrated with a heating unit and infrared lamp for drying paddy grains and the authors found that the energy consumption in the solar-assisted drying process was 0.314 kWh, whereas the energy consumption in the natural gas drying mode was 1.163 kWh [86]. Hence, the authors concluded that energy consumption reduced by solar drying. Seerangurayar et al. (2019) investigated the drying characteristics of dates by three different modes namely, drying in direct sun, greenhouse tunnel dryer, and forced convection dryer. They also found that the shrinkage of dates was less with better quality while drying in forced convection dryer [87]. Zaineb et al. (2020) investigated the drying characteristics of a mixed-mode drying unit with and without energy storage and the authors concluded that the drying rate decreased while using the dryer with an energy storage medium [88]. Baghel and Chander (2022) investigated the performance of photovoltaic modules in various weather conditions and evaluated the energy trapped [89]. Ruben Bartali et al. (2023) analyzed the performance of an evacuated tube solar collector using carnauba wax [90].

C. *Optimization of Solar Dryers*

Various researchers had developed various mathematical models to analyze the various thermal behaviour of various solar dryers, and they are presented in this section. Sharma et al. (1991) designed a model using a simultaneous heat transfer concept to determine the performance of a cabinet type dryer [91]. Janjai et al. (1994) formulated a simulation model to evaluate the optimum collector area of a forced convective dryer for paddy grains drying [92]. Onyegegbu et al. (1994) developed an optimization model for various ambient conditions for an integrated type of natural convection crop drying system using solar energy [93]. Tiwari et al. (1994) developed energy balance equations to estimate the design parameters of a passive type dryer fitted with a reflector for crop drying and the authors found that the drying time considerably decreased [94]. Sharma et al. (1994) conducted an economic analysis of air heating units for crop drying [95]. Schoenau et al. (1995) formulated a simulation model to optimize the different energy systems for drying canola grain and estimated the drying time, energy consumption, and spoilage index for different energy systems, and the authors found that the solar energy system was more cost-effective [96]. Mumba (1995) conducted an economic analysis of a passive dryer for crop drying [97]. Tiwari et al. (1997) developed an energy balance equation for a dryer incorporated with a water heater to ensure the operation of the drying unit throughout the year [98]. Balladin et al. (1997) evaluated the pungent principles of West Indian sliced ginger dried using solar energy [99].

McDoom et al. (1999) investigated the energy consumption in various operating modes of a solar dryer for crop drying [100]. Goyal and Tiwari (1999) formulated energy balance equations to analyze the thermal performance of cabinet-type reverse flat plate collectors for crop drying [101]. Riyad and

Jacques (2001) developed a simulation model to optimize the functionality of a forced convective dryer for drying crops and the authors found that the drying time reduced from 52 hours to 44 hours [102]. Donka and Kondju (2001) developed a model to determine the variation in air temperature and humidity in the combined fruit and vegetable dryer [103]. Osman et al. (2001) developed a model to analyze the influence of drying air temperature and velocity of a forced convective dryer integrated with a cabinet for grapes drying in Turkey [104]. Dilip and Tiwari (2004) formulated a simulation model to examine the thermal behaviour of natural and forced convective dryers for crop drying and the authors validated the results of the model with an experiment [105]. Subsequently, these authors evaluated the convective mass transfer coefficient of natural and forced convection crop dryers in the year 2004 [106]. Siham et al. (2004) formulated a model to analyze the influence of air temperature on the drying time using a forced convective dryer with a cabinet for sliced pear drying [107]. Hossain et al. (2005) developed an optimization model using adaptive pattern search to determine the optimal sizes of the tunnel dryer using solar energy for chilli drying in Bangladesh [108]. Hamdy (2006) developed an empirical model to study the drying behaviour of seedless grapes in a solar drying chamber [109]. Kavak and Bicer (2008) developed a model to determine drying characteristics of indirect type forced convective dryer for long green pepper drying [110]. Kamenan (2009) et al. developed an empirical model to analyze the major drying parameters of a direct mode dryer for fruit drying [111].

Kavak (2010) analyzed the thermal performance of an indirect forced convective drying and natural convective direct drying of mint leaves and the authors found that the exergy efficiency lies between 34.760% and 87.717% [112]. Agnieszka and Krzysztof (2010) evaluated drying models to evaluate the drying behaviour of various shapes of red beetroot slices using a laboratory-type solar dryer [113]. Dissa et al. (2011) developed models to examine the drying characteristics of direct solar drying for drying different varieties of mangoes [114]. Serm et al. (2011) formulated models to estimate the thermal performance of a greenhouse parabolic-shaped dryer for fruits and vegetable drying using solar energy [115]. Afriyie et al. (2013) set up a model to study the drying characteristics of dryers integrated with chimneys for crop drying [116]. Shobhana and Subodh (2013) developed a model to estimate the various performance parameters of a mixed-mode dryer for sliced potato drying and the authors found that the dryer is capable of maximum CO_2 emission mitigation [117]. Ahmad (2013) formulated a model to study the influence of acoustic and solar energy on pistachios drying assisted by ultrasound [118]. Wei and Man (2014) investigated the heat transfer characteristics of an indirect mode solar dryer having a porous absorber integrated with a chimney [119]. Altobelli et al. (2014) studied the various indicators of drying potential which influence the solar dryer efficiency in Argentina [120]. Ines et al. (2015) developed heat transfer relations to examine the drying characteristics of grapes in a mixed-mode dryer [121]. Sumit and Tiwari (2016) assessed the thermal behaviour of photovoltaic-thermal greenhouse dryers [122]. Subsequently, in the year 2016, the authors conducted exergoeconomic studies in the greenhouse dryer [123]. Yu et al. (2016) examined the thermal characteristics of a heat pump drying unit integrated with a heat recovery unit [124]. Sumit et al. (2016) analyzed the performance of photovoltaic–thermal greenhouse dryer using solar energy and estimated the drying efficiency [125]. Prashant and Anil (2017) analyzed the heat transfer characteristics of a natural convective greenhouse dryer and determined the performance indicators [126]. Cristiana et al. (2017) analyzed the drying parameters for bananas drying using solar energy in an updraft tower in Brazil and the authors found that the exergy efficiency increased from 20% to 27% with the load [127].

Vineet et al. (2017) discussed the various parameters of the environment on a forced convective greenhouse dryer with photovoltaic systems [128]. Morad et al. (2017) investigated the behaviour of a tunnel-type forced convective greenhouse dryer for peppermint drying and the authors concluded that the drying rate was improved by 22.78% [129]. Halil et al. (2017) formulated a model to estimate the drying rate of sliced apples in a solar dryer incorporated with an energy storage unit [130]. Abhay et al. (2018) analyzed the heat transfer characteristics in an indirect type solar air heating system fitted with a square-shaped rib over the absorber plate for crop drying [131]. Prashant et al. (2018) designed a model to estimate the drying kinetics of bitter gourd in a greenhouse dryer [132]. Simona et al. (2018) studied a combined heat and power unit using solar energy and biogas for sewage sludge drying and the authors found the thermal efficiency of the combined unit was 44%, whereas the efficiency of the solar unit was 56% [133]. Wengang et al. (2018) evaluated the

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thermal behaviour of flat plate collectors for crop drying and the authors reached the conclusion that the thermal efficiency of the dryer varies between 32.5% to 50.8% [134]. Prashant et al. (2018) examined the drying kinetics of sliced bitter gourd in a greenhouse dryer under free and forced convection [135]. Mohamed et al. (2018) studied the thermal characteristics of a mixed-mode tunnel type dryer powered by the solar photovoltaic system for potato drying and the authors recognized that the drying efficiency of the collector without a thermal curtain was 28.49%, whereas the efficiency increased to 34.29% with thermal curtain [136]. Baher et al. (2018) examined an integrated hybrid drying unit for drying chamomile in Germany [137]. Ouassila et al. (2019) analyzed the drying kinetics of waste tomato pomace in a greenhouse dryer and the authors found that drying was achieved between 40 and 58 °C [138]. Khouya and Draoui (2019) developed a model for the solar kiln for wood drying and the authors found that the maximum drying efficiency was 85% [139]. Younes et al. (2019) discussed the thin layer drying behaviour of medicinal plants under free and forced convection solar drying [140].

Sameh et al. (2019) estimated the collector thermal efficiency fabricated with recycled aluminium for crop drying and the authors found that the efficiency increased from 25% to 63% [141]. Akbar et al. (2019) estimated the exergy efficiency of a dryer provided with a porous and recycling unit and the authors found that the collector attained an exergy efficiency of 22.3% [142]. Kuan et al. (2019) developed a model to estimate the energy performance of a dryer incorporated with a heat pump for continental weather conditions [143]. Mehrnush et al. (2019) investigated the thermal characteristics of a dryer to preserve food items, and they found that the average drying efficiency was nearly 51%, 53%, and 54% for the non-porous unit, porous unit, and porous and recycling unit, respectively [144]. Ahmed et al. (2019) studied the behaviour of sliced tomatoes drying in a mixed-mode dryer [145]. Rim et al. (2020) formulated a dynamic model to estimate the thermal characteristics of a greenhouse drying unit for crop drying [146]. Ahmed et al. (2020) examined the drying characteristics of sliced potatoes in an indirect and a mixed mode forced convective dryer [147]. Divyangkumar et al. (2024) conducted a sustainability study of various dryers and proposed the selection criteria of solar dryers [148].

D. Recent Developments

Recent developments on solar drying for crops are presented in this section. Garg et al. (1984) developed and studied the thermal characteristics of a solar dehydrator for crops drying [149]. Muhlbauer (1986) reviewed the significant developments in various solar drying systems for fruit and vegetable drying [150]. Thanvi and Pande (1987) developed an economic solar dryer for drying crops in India and the authors found the drying time was considerably decreased by using the newly developed dryer [151]. Eddy et al. (1991) developed a tunnel-type dryer using solar energy for usage in tropical regions and the authors found that the drying time reduced by 40% [152]. Chakraverty and Das (1992) developed a bi-directional airflow solar dryer integrated with collector modules for paddy drying [153]. Breymayer et al. (1993) developed a rubber dryer using solar energy in Indonesia and the authors found the drying time reduced with improved quality of rubber [154]. Mumba (1996) developed a dryer with photovoltaic cells for drying grains in rural applications [155]. Thoruwa et al. (1996) developed a forced convective dryer with regeneration for drying crops in rural areas in Kenya [156]. Ekechukwu and Norton (1999) have conducted a study about various types of dryers. One among them is the greenhouse dryer with chimney which is illustrated in figure 6 [157].

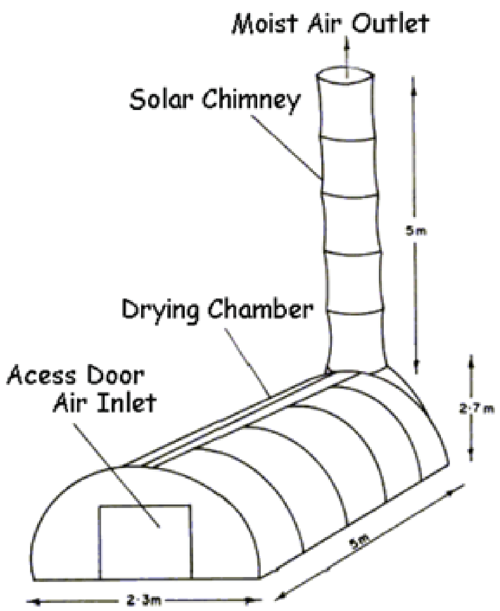

Fig. 6. Greenhouse solar dryer with chimney [157]

Wisniewski (1999) studied the developments of solar flat plate collectors for crop drying in European countries [158]. Othman et al. (2006) developed dryers of various configurations using solar energy for crop drying in Malaysia [159]. Sarsavadia (2007) developed a forced convective flat plate dryer for drying sliced onion and the author found that the energy saved was 70.7% [160]. Forson et al. (2007) developed a mixed-mode free convective dryer for drying crops and the authors found that the drying efficiency was 12.3% [161]. Montero et al. (2010) investigated the functional characteristics of a dryer in various modes of operation for agro-industrial derivatives drying in Spain [162].

Blake et al. (2014) developed a concentrating dryer for drying tomatoes and the authors found the drying time reduced by 21% [163]. Yahya et al. (2016) investigated the thermal characteristics of a dryer incorporated with a heat pump for drying cassava and the authors found that the attained thermal efficiency was 30.9% with a maximum pick-up efficiency of 70.4% [164]. Abubakar et al. (2018) analyzed a mixed-mode dryer with and without energy storage for crops drying in Nigeria. The authors found that the attained collector efficiencies with and without energy storage were 67.25% and 40.10%, correspondingly [165]. Panli et al. (2019) developed a novel drying method for sewage sludge disposal and the authors concluded that the drying time considerably reduced [166]. Messaoud et al. (2019) developed an improved dryer with a geothermal heating unit in Algeria [167]. Amjad et al. (2023) reviewed the recent developments in solar cooling systems for agricultural products [168].

III. FINDINGS

Table 1 illustrates the performance and characteristics of various dryers for crops drying. Table 2 illustrates the moisture removal rate of different types of dryers for crops drying. It is identified that two broad groups of dryers namely, natural and forced convection dryers, are used for agricultural product drying. It is also identified these two categories of solar dryers are further categorized as high-temperature dryers, low-temperature dryers, open to sun dryers, hybrid dryers, direct solar dryers, indirect solar dryers, integral dryers, distributed mode dryers, and mixed-mode dryers. It is also identified that the thermal performance and the drying characteristics of the forced convective dryers are superior to natural convection and greenhouse dryers. From the results of the experiments conducted in various countries, it is identified that solar dryers are used very effectively for agricultural product drying.

TABLE I. PERFORMANCE AND DRYING CHARACTERISTICS OF VARIUOS TYPES OF SOLAR DRYERS

Author (Year)	Types of Solar Dryer	Agricultural Product	Performance and Drying Characteristics
Alvin et al. (1985)	Suspended-plate solar air heater	Agricultural Crops	- Thermal efficiency: 50–70%.
Ezeike (1986)	Triple pass flat plate air collector	Rice paddy and yam slices	- Collector efficiency: 73–81%.
Miguel and Luis (1998)	Forced convection greenhouse driers	Red pepper	- Productivity improvement: 90%.
McDoom et al. (1999)	Scaled-down dryer	Coconut and cocoa	- Energy-saving: 29 to 31%.
Hossain et al. (2005)	Tunnel type solar drier	Chilli	- Cost-saving: 15.9%.
Sarsavadia (2007)	Forced convection solar dryer	Onion	- Maximum energy saving: 70.7%.
Sujata and Tiwari (2008)	PV/T integrated greenhouse dryer	Crops drying	- Exergy efficiency: 4%.
Amer et al. (2010)	Hybrid solar dryer	Banana	- Solar dryer efficiency: 65%.
Kavak (2010)	Forced convective indirect solar dryer	Mint leaves	- Energy utilization ratio: 7.826% to 46.285%. - Exergy efficiency: 34.760 to 87.717%.
Wisut et al. (2013)	Desiccant Bed Solar Dryer with dehumidification	chilli	- Collector efficiency: 42.1 %. - Chamber efficiency: 13.8 %.
David and Ángel (2014)	Hybrid dryer	Pineapple	- Evaporation efficiency: 9.3% to 14.0%.
Seyfi (2014)	Heat pump solar dryer	Fruits and vegetables	- Thermal efficiency: 16% to 79%. - Energy utilization ratio: 0.19 to 0.48.

Ahmad et al. (2015)	Forced convection solar dryer	Palm oil fronds	- Collector efficiency: 31%. - Drying system efficiency: 19%. - Pick-up efficiency: 67%. - Average exergy efficiency: 47%.
Misha et al. (2015)	Solid desiccant dryer	Kenaf	- Dryer efficiency: 12%.
Nabnean et al. (2016)	Cabinet type dryer	Cherry tomatoes	- Collector efficiency: 21% to 69%.
Yu Qiu et al. (2016)	Solar aided heat pump dryer	Radish, pepper and mushroom	- Coefficient of performance: 3.21 to 3.49. - Energy-saving: 40.53%.
Sekyere et al. (2016)	Mixed-mode natural convective dryer	Crops	- Moisture pickup efficiency: 11% to 32%.
Roonak and Abdellah (2016)	Evacuated tube heat pipe dryer	Crops	- Exergy efficiency: 11.7%.
Fevzi et al. (2016)	Solar air collector	Sweet basil	- Collector efficiency: 63%.
Tadahmun and Hussain (2016)	Hybrid dryer with the waste heat recovery unit	Red chilli	- Overall drying efficiency: 13%.
Karunaraja et al. (2017)	Solar tunnel dryer with thermal energy storage	Vitis vinifera & Momordica charantia	- Thermal efficiency: 15.46%.
Cristiana et al. (2017)	Updraft solar tower	Banana	- Exergy efficiency: 20% to 27%.
Sumit and Tiwari (2017)	Mixed mode greenhouse solar dryer	Crops	- Thermal efficiency: 61.56% to 42.22%. - Exergy efficiency: 28.96% to 19.11%.
Aymen et al. (2017)	Indirect forced convective dryer	Heat storage	- Energy efficiency: 33.9%. - Exergy efficiency: 8.5%.
Mustafa et al. (2017)	Hybrid dryer	Grated carrot	- Maximum exergy efficiency: 66.8%. - Minimum exergy efficiency: 31.6%. - Energy efficiency: 5.3 to 50%.
Ndukwu et al. (2017)	Natural convection dryer with energy storage	chilli	- Overall drying efficiency: 10.61 to 18.79%. - Exergy efficiency: 66.79 to 96.09%.
Ehsan et al. (2017)	Mixed-mode dryer	Crops	- Moisture pick-up efficiency: 10%. - Thermal efficiency: 11%.
Kareem et al. (2017)	Multi-pass solar dryer	Screw-pine	- Instantaneous thermal collector efficiency: 22% to 26%. - Pickup efficiency: 66.95%. - Drying efficiency: 36.04%. - Exergy efficiency: 27.23–86.82%.
Kareem et al. (2017)	Multi-pass air heating system.	Roselle	- Optical efficiency: 70.53%. - Collector efficiency: 64.08%. - Drying efficiency: 36.22%. - Moisture pickup efficiency: 66.95%
Abubakar et al. (2018)	Mixed mode dryer	Crops	- Average drying rate: 2.71 × 10−5 kg/s (With thermal storage), 2.35 × 10−5 kg/s (Without thermal storage). - Collector efficiency: 40.10 to 67.25 %. - Drying efficiency: 24.20 to 28.75%.
Lakshmi et al. (2018)	Mixed-mode dryer	Turmeric	- Overall efficiency: 12%.
Karthikeyan and Murugavelh (2018)	Mixed mode forced convective tunnel dryer	Turmeric	- Exergy efficiency: 23.25 to 73.31%.
Simona et al. (2018)	Combined heat and power integrated with solar dryer	Sewage sludge drying	- Thermal efficiency: 44.0%. - Primary energy saving: 14.6%.
Prashant et al. (2018)	Greenhouse dryer with PV cells	Crops	- Exergy efficiency: 21.4%. - Heat utilisation factor: 10.1%. - Coefficient of performance: 7.9%.
Wengang et al. (2018)	Dual function flat plate solar collector	Agricultural products	- Heat collecting efficiency: 32.5% to 50.8%. - Heat loss coefficient: 2.5 to 6.2 W/(K m^2).
Mohamed et al. (2018)	Tunnel type mixed-mode dryer	Potato chips	- Drying efficiency: 34.29%.

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Panli et al. (2019)	Solar dryer with chamber beds	Sewage sludge	- Average drying rate: 6.72 g/h.
Khouya and Draoui (2019)	Solar kiln with latent heat storage	Wood	- Energy-saving: 482 KWh. - Drying efficiency: 85%.
Sameh et al. (2019)	Dryer with recyclable aluminium	Agricultural products	- Thermal efficiency: 63%.
Akbar et al. (2019)	Dryer with a porous and recycling unit	Crops	- Energy efficiency: 19.1%. - Exergy efficiency: 19.5%.
Kuan et al. (2019)	Dryer incorporated with heat pump	Banana	- Moisture removal rate: 0.6 kg/kWh. - Coefficient of performance: 2.72.
Mehrnush et al. (2019)	Solar collector with porous medium and recycling unit	Crops	- Average drying efficiency (non-porous system): 51%. - Average drying efficiency (porous system): 53%. - Average drying efficiency (porous and recycling system): 54%.
Lopez-Vidana et al. (2020)	Passive mixed-mode dryer	Tomato slices	- Collector efficiency: 52.30% to 55.45%. - Overall dryer efficiency: 10.66%. - Drying efficiency: 5.47%.
Dutta et al. (2023)	Multi-mode dryer with sensible heat storage	Garcinia pedunculata	- Drying efficiencies: 18.55% to 29.94%.

TABLE II. MOISTURE REMOVAL RATE WITH RESPECT TO LOAD FOR VARIUOS TYPES OF SOLAR COLLECTORS

Author (Year)	Solar Dryer Type	Agricultural Product	Load	Drying Time	Moisture Removal Rate
Das and Kumar (1989)	Dryer integrated with chimney	Paddy grains	20 kg	9 hours	31 to 13% (db).
Chakraverty and Das (1992)	Bidirectional modular type solar dryer	Raw paddy	500 kg	3.5 hours	23.5 to 14% (db).
Mumba (1996)	PV cell incorporated solar dryer	Maize	90 kg	24 hours	33.3 to 20% (db).
Thoruwa et al. (1996)	Forced circulation dryer with desiccant medium	Maize	90 kg	24 hours	38 to 15% (dwb).
Forson et al. (2007)	Mixed-mode natural convective dryer	Cassava	160 kg	30–36 hours	67 to 17% (wb).
Sreekumar et al. (2008)	Indirect mode cabinet dryer	Bitter gourd	4 kg	6 hours	95 to 5%.
Amer et al. (2010)	Hybrid solar dryer	Banana	30 kg	8 hours	82 to 18% (wb).
Wisut et al. (2013)	Desiccant Bed Solar Dryer	Chilli	8 kg	24 hours	82 to 13% (wb).
Samira et al. (2014)	Direct natural convection drier	Deglet-Nour Dates	1 kg	22 hours	0.5 to 0.35 (kg water/kg dry matter).
Ahmad et al. (2014)	Solar air heating system	Red seaweed		15 hours	90 to 10% (wb).
Ahmad et al. (2015)	Forced convection solar dryer	Palm oil fronds	100 kg	22 hours	60 to 10% (wb).
Misha et al. (2015)	Solid desiccant dryer	Kenaf	Five trays of sample	2 days	Final moisture content: 18%.
Yahya et al. (2016)	Dryer incorporated with heat pump	Cassava chips	30.8 kg	i) 13 hours at 40 °C. ii) 9 hours at 45 °C	61 to 10.5 % (wb).
Karunaraja et al. (2017)	Solar tunnel dryer with thermal energy storage	Vitis vinifera & Momordica charantia	20 kg	i) 27 hours ii) 6 hours	85 to 10%. 88 to 6%.

Lakshmi et al. (2018)	Forced convective dryer	Turmeric	200 g	18.5 hours	73.4 to 8.5% (wb).
Baher et al. (2018)	Hybrid solar dryer	Chamomile	32–35 kg	30 to 33 hours	72 to 6% (wb).
Karthikeyan and Murugavelh (2018)	Mixed mode forced convective tunnel dryer	Turmeric	1 kg	12 hours	0.779 to 0.070 (kg water/ kg dry matter).

IV. CRITICAL REVIEW AND DISCUSSION

The following section gives insight about the critical review of the references mentioned in the manuscript. The result outcomes of each research cannot be compared to one another, since a unique experimental set up has been employed, which is the limitation of the present study. Also, it is worth mentioning that every researcher has carried out the experiments targeting different measuring outputs, hence it is not possible to compare the same output parameter for all studies. The economic point of view is not considered in this review article, since very few researchers have addressed it striking a comparison between all studies given the limited available resources may not give the actual desired results.

David Gudino-Ayala et al. [70] compared two types of solar dryer namely traditional and hybrid dryers to dry pineapple. They found that the evaporation efficiency was attained in ranges between 22.7% and 24.0% for traditional dryer, whereas for the hybrid method it was found between 9.3% and 14.0%. On the other hand, time taken was less in case of hybrid dryer when compared to traditional one. Evaporator efficiency and time taken to attain theses efficiencies were plotted as shown in figure 7.

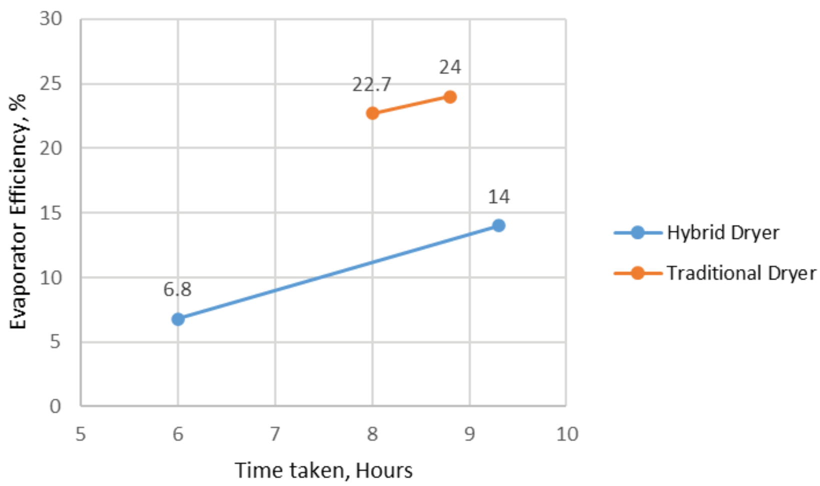

Fig. 7. Drying time vs evaporator efficiency traditional and hybrid solar dryer

A comparative assessment of forced and natural convection of an indirect type solar dryer using green chili was done by Mugi et al. [55]. Fans powered by PV panels were used for forced convection setup. The average drying efficiencies were found to be between 10.4 % and 8.9 % under forced and natural convection methods. Whereas collector efficiency was found to be between 63.3 % and 53.84%, respectively. From the results obtained, it is evident that for both the drying and collector efficiencies, they were established to be higher in case of a forced convection setup than the natural convection.

The thermal efficiency attained by various drying techniques is depicted in figure 8. Tiris et al. [13] used an experimental set up with air heater and a drying chamber. While, Ezeike [5] used triple-pass solar collector and dryer system, both attained a thermal efficiency around 80 %, whereas the least was around 11 % in case of mixed mode solar dryer [80]. Several other dryer types such as natural convection dryer, collector made with recycled aluminium cans, PV integrated greenhouse dryer and heat pump drying techniques also exhibited significant efficiencies as shown in figure 8.

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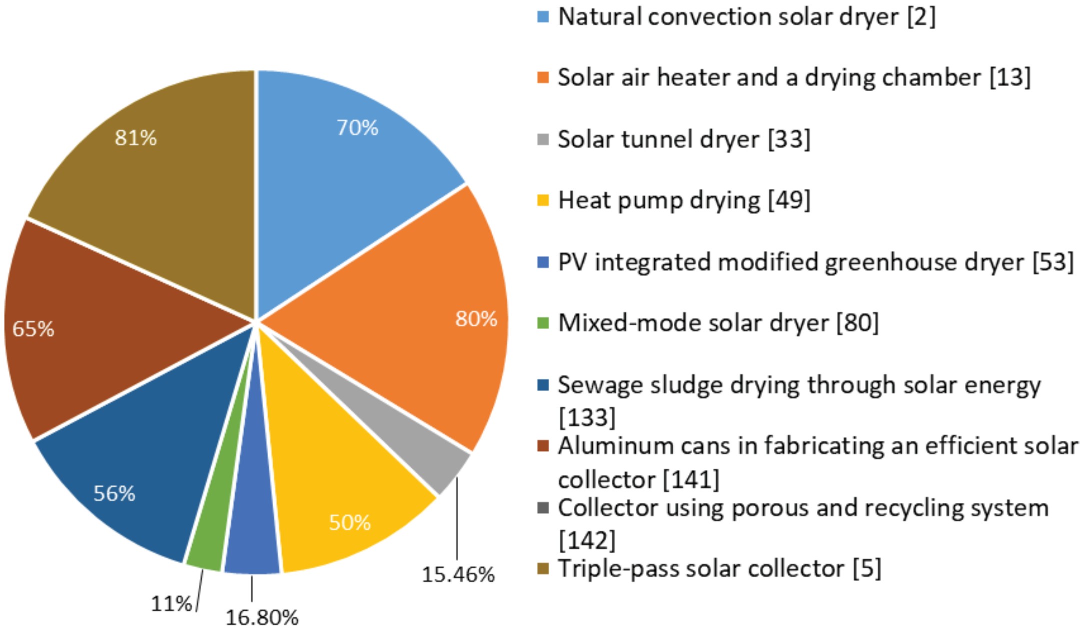

Fig. 8. Types of drying methods and attained thermal efficiencies

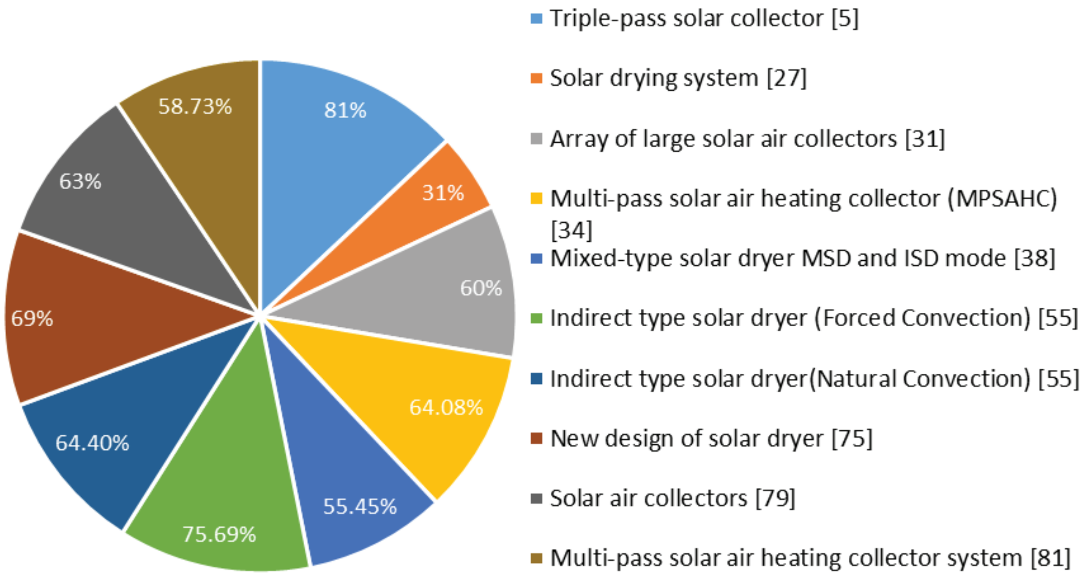

Fig. 9. Types of drying methods and attained collector efficiencies

Solar collectors are special kind of heat exchangers which are used to convert direct and diffuse radiation from the sun into useful thermal energy. Collector efficiency of various experimental set up is presented in figure 9. It is evident that the maximum collector efficiency of around 81 % was attained by the method which employs triple pass solar collector [5]. On the other hand, the least collector efficiency was accomplished as 31 % in case of a conventional drying system [27]. A remarkable efficiency of 75.69 % was attained by Mugi et al. [55] using an indirect type dryer with forced convection, while the collector efficiency was around 55.45 % with a natural convective indirect dryer. With forced and natural convection, a difference of around 20 % collector efficiency was noticed with the same experimental setup.

Most researchers have evaluated the moisture removal rate since it contributes to the overall efficiency of the dryer. Moisture removal rate for various dryer types is shown in figure 10.

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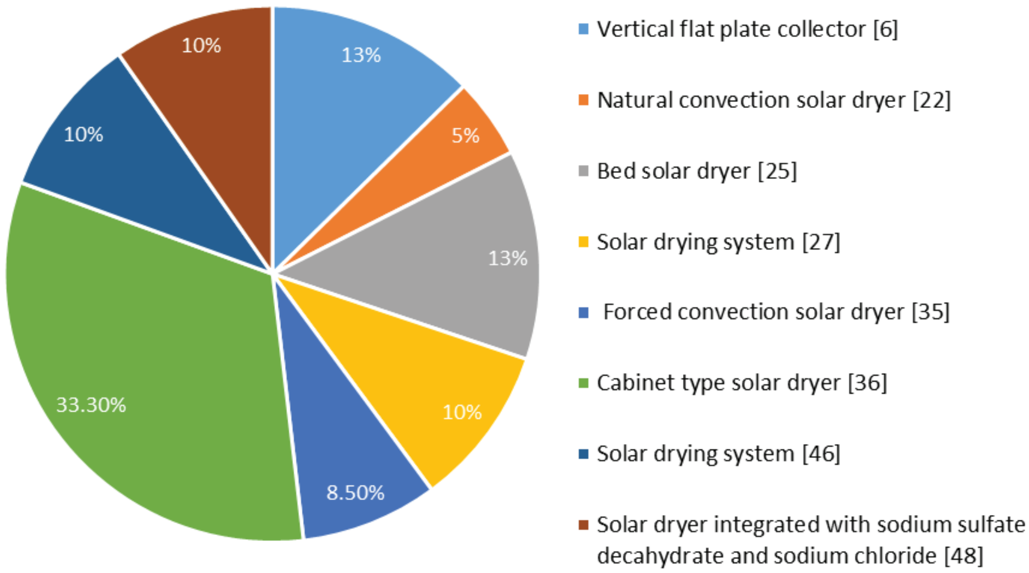

Fig. 10. Moisture removal rate of different dryers

Figure 10 illustrates the moisture removal rate of different dryers. The same is elaborated in the following section. A maximum moisture was removed from 95 % to 5 % in 5 hours while using the natural convection dryer [22]. A similar rate was achieved with indirect forced convection dryer (i.e) 10% from 90 % in 15 hours [46]. Though the rate of achievement was almost same, but with a time difference of almost 10 hours. But while using the forced convection technique, the moisture removal was 73.4 % to 8.5 % in 18.5 hours [35]. An average of 10 % was achieved by 72.27% moisture using a dryer integrated with sodium sulfate dehydrate and sodium chloride as energy storage medium [48].

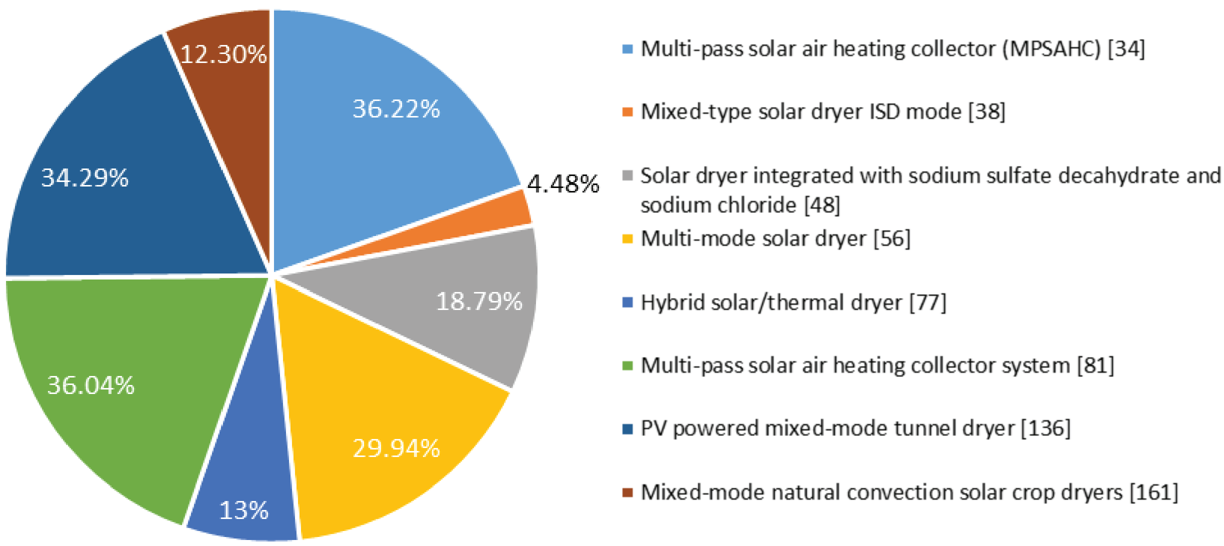

Fig. 11. Drying efficiency of different solar dryers

Figure 11 illustrates the drying efficiency of different dryers. A maximum drying efficiency of 36 % was achieved by Kareem et al. [34 & 81]. They used a multi pass air heating system to dry hibiscus sabdariffa and screw-pine leaf, whereas the least drying efficiency was found to be 4.48 % by using mixed-type solar dryer. Indirect Solar Dryer (ISD) mode was experimented by Cesar [38] using mixed type dryer to dry tomato slices. Dutta et al. [56] used a novel multi-mode dryer and attained a dryer efficiency of around 30 % in 8 hours.

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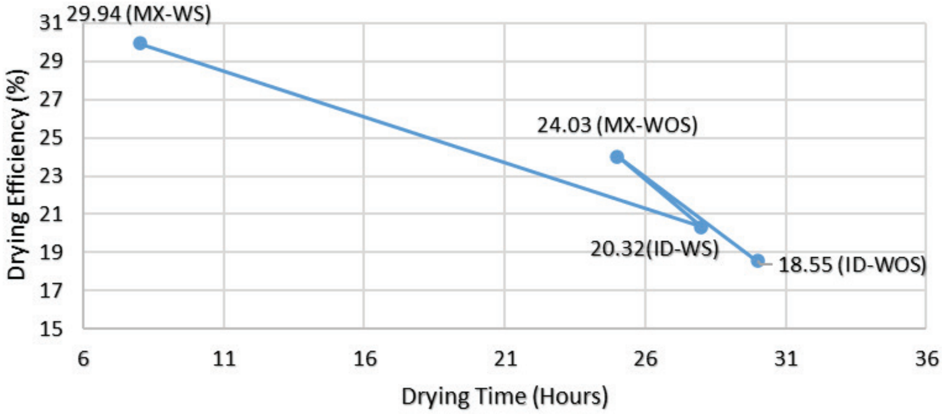

Fig. 12. Drying time vs drying efficiency of different modes of dryers

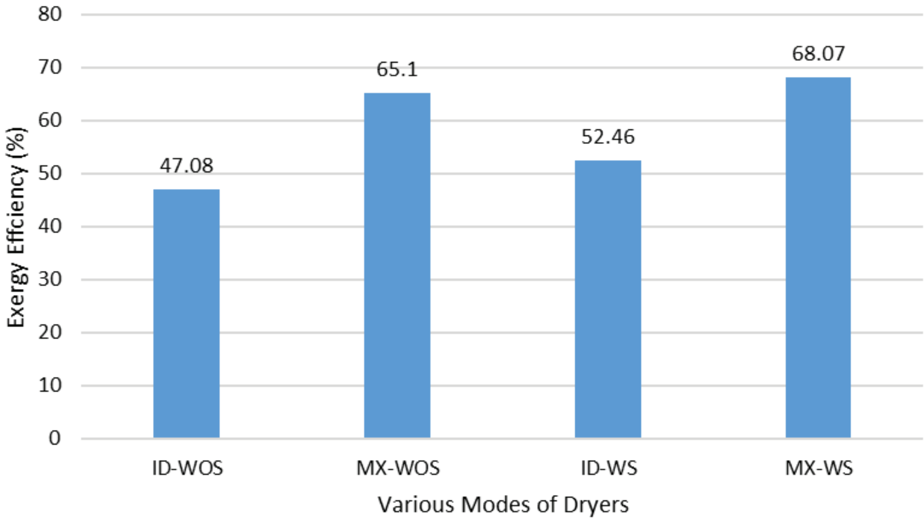

Fig. 13. Exergy efficiency of various modes of dryers

Dutta et al. [56] investigated the drying time of Garcinia pedunculata using a novel four-mode dryer namely indirect-mode without storage (ID-WOS), mixed-mode without storage (MX-WOS), indirect-mode with storage (ID-WS), and mixed-mode with storage (MX-WS). From figure 12, it was found that the drying time and drying efficiency for each type of dryer is different. Maximum efficiency of almost 30 % was obtained in just 8 hours of drying by employing MX-WS type dryer. The least drying efficiency was found to be 18.5 % in 30 hours using ID-WOS type dryer. The authors also concluded that the average exergy efficiency was found to be 47.08 %, 65.10 %, 52.46 %, and 68.07 % for the above-mentioned dryers as shown in figure 13.

V. CONCLUSION

A comprehensive review of the various designs, construction details and performance parameters of the wide variety of solar air heating systems is presented. In addition, the various categories of solar dryers for agricultural products drying have been reviewed and presented in a comprehensive manner. Two broad groups of solar dryers namely, natural and forced convection dryers, are identified. It has become clear that these two categories of solar dryers are further categorized as integral type dryers, distributed mode dryers and mixed-mode dryers. It is also concluded that the thermal performance and the drying characteristics of the forced convective dryers are superior to natural convection dryers and greenhouse dryers. Wider range of geographical location shall be included in the future scope for more comprehensive studies. From the results of the experiments conducted in various countries, it has become evident that solar dryers are used very effectively for agricultural product drying.

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