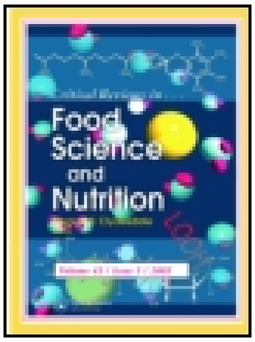

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REVIEW

Sustainable food drying technologies based on renewable energy sources

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ABSTRACT
Waste in the food supply chain is estimated to be about 30–40% of the total food production, which aggravates the world hunger and increases waste management burden and environmental impact. Despite the dire food scarcity, majority of this food waste takes place in developing countries because of the lack of appropriate and affordable preservation techniques. Traditional open sun drying is the most popular food-reservation technique to the local farmers due to near-zero capital cost and cheap labor cost. However, this method is highly energy intensive, unhygienic, and time demanding. The high energy consumption resulting from uncontrolled simultaneous heat, mass, and momentum transfer processes in traditional drying systems highlights the necessity of pursuing sustainability in drying process targeting reduced energy consumption, environmental and social impacts. This paper presents a comprehensive review on the sustainable food drying technologies based on renewable energy sources, with emphasis on the developing countries. It was observed that the integration of thermal energy storage with heat pump makes the integrated drying system more efficient, and dries food with better quality. Likewise, advanced integrated drying systems, such as, solar with microwave, and heat pump with microwave make the drying process more cost and quality competent. Finally, impact of resource distribution and governmental incentives for renewable energy use in sustainable drying is discussed.

KEYWORDS
Food drying; solar drying; microwave drying; thermal storage; renewable energy; sustainable drying

1. Introduction

Almost one third of the harvested food is wasted due to the lack of proper post-harvest processing (Ghnimi et al. 2017). Such enormous food wastage is unacceptable as nearly a billion people suffer from acute hunger and are deprived of adequate nutrition in the low-income developing and least developed countries (Karim and Hawlader 2005a). Besides, the demand for energy, infrastructure, and resource management in each stage from harvesting to wastage handling bring immense burden to the farmers, producers, businesses and governments. In the developing countries poor post-harvest (from farm to retailer) food processing contribute to this food waste. Drying is the dominant food preservation method and practiced worldwide (Khan and Karim 2017; Masud et al. 2020). However, current industrial food drying systems are mostly energy intensive process, which accounts up to 25% of all industrial usage (Karim and Hawlader 2005b). The problem of high energy consumption is mainly due to the lack of fundamental understanding of drying processes including microscale morphological changes during drying (Khan, Farrell, et al. 2018; Khan, Nagy, and Karim 2018) and their effect on product and process design. Moreover, lack of appropriate properties is one of the major obstacles to develop energy efficient food drying system (Khan et al. 2021).

A typical convective dryer can be less than 50% efficient even if it is well designed and properly operated (Tsotsas and Mujumdar 2011). Most of the developing countries have been facing a substantial energy crisis. These countries cannot afford conventional drying technologies due to their energy limitation. Therefore, balance between the efficiency, quality, and the cost of food drying should be emphasized (Joardder et al. 2015). Drying technologies with low fossil-based energy requirement are most appropriate methods for developing countries as they are rich in renewable energy resources (Masud et al. 2020). However, application of these sustainable energy resources (e.g., solar, geothermal, biomass) in different drying technologies demand significant scientific studies. In applying solar energy in food drying (Islam et al. 2019), designing an efficient collector play a significant role (Islam et al. 2017; Islam, Yarlagadda, and Karim 2019). Recent studies show that application of nanofluids significantly increases the performance of solar collectors (Karim et al. 2019; Karim et al. 2020).

The trend of food waste is related to the characteristics of individual food material. Studies show that plant-based food

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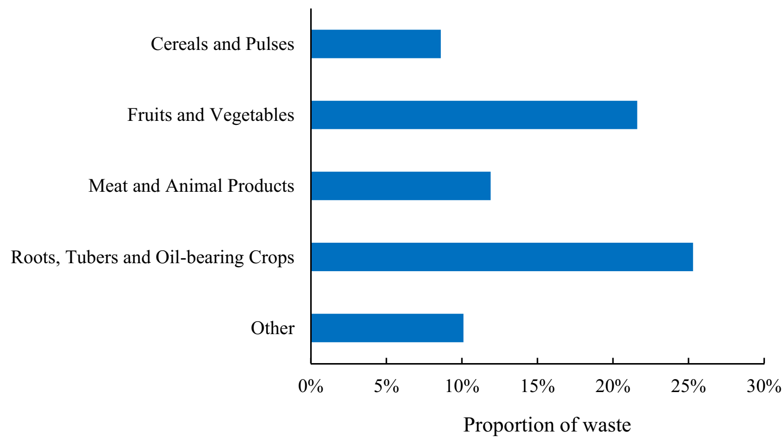

Figure 1. Global food losses by commodity groups estimated in 2016.

materials with high water content are more perishable than other food materials. For instance, postharvest waste of roots and tubers crops was reported to be 25.3%, and fruits and vegetables was 21.6% worldwide in 2016 (refer to Figure 1) (FAO 2019a). However, this study did not include the losses that take place in the farm before harvesting, and at the households before selling into market. Being highly perishable in nature, waste of fruits and vegetables are very high in the harvesting season. In the first group, cassava and potato are the most perishable crops that constitute the major proportion of the wastage in that group. Cassava can start perishing within two or three days of harvesting, while potato can easily get deteriorated under humid and warm climates which are typical in many developing countries in South Asia (FAO 2019a).

Each foodstuff has unique characteristic (Khan, Joardder, et al. 2018) that requires customized dryer for efficient and economic drying needs. Cereal, for instance, has relatively low initial moisture content (25%, wet basis) and requires drying to 8–10% of moisture content. In addition, they are normally free flowing and produced in large quantity, thus are suitable for batch or circulatory dryers (FAO 2019b; Patil and Shukla 2006). Fruits and vegetables are the extremely important sources of daily nutrition of human body, such as, vitamins, minerals and fiber (Duc Pham et al. 2019; Pham, Khan, and Karim 2020). Storage of these fruits and vegetables needs adequate cold storage facilities. However, most farmers are deprived of basic energy (such as, electricity) need, and rely on open sun drying instead of cold storage for their produce preservation (Joardder, Mandal, and Masud 2020). Therefore, an efficient and renewable energy-based drying system could be a sustainable solution for the long term food preservation in developing countries (Jairaj, Singh, and Srikant 2009).

Dried sultana is by far the main dried fruit consumed globally. Other major dried fruits are dates, mangoes, apricot, banana, apple and pineapple (Hii et al. 2012). These fruits can be dried in different shapes such as slices, halves or even whole depending on the consumers' demand. Based on their unique characteristics, required moisture content of the dried fruits varies between 3% and 18% (Sinha et al. 2012). More than 80% of agro-based food produces are being produced by small farmers in developing countries (Murthy 2009). These farmers widely use open sun drying to preserve their surplus harvest, without much considerations for the quality degradation due to the insects, dirt and rain etc. Certain variety of fruit even lose their basic characteristics (i.e., color, smell and taste) in the presence of sun light, and therefore, not suitable for open-air sun drying. Therefore, open air sun drying, though the energy is free of cost, is not economically viable for many of the food stuffs.

Solar drying is widely used for the postharvest processing of agricultural products (Karim, Perez, and Amin 2014). However, simple solar dying systems are dependent on the intermittent nature of solar radiation, and therefore, reliable and continuous output of the system cannot be achieved. Thermal storage enables continued operation at the off-sunshine time and cloudy day, hence, make the solar dryer uninterrupted (Karim et al. 2018; Kant et al. 2016). Amer, Gottschalk, and Hossain (2018) developed a solar chamomile drying system integrated with water tank as supplement and reported a drying time of 30–33 hours in German weather, much more effective compared with 60 hours of open sun drying system. To ensure uninterrupted drying, an electric heater was installed in the water tank.

In solar drying, the food material exposes to drying medium driven through the chamber by the convective force (Karim and Hawlader 2005b). However, solar drying is a convective drying, and therefore, require longer drying time resulting in poor product quality at elevated temperatures (Zhang et al. 2006). Compared to these conventional dryers, microwave (MW) integrated drying technology offers many advantages including faster drying process and energy saving due to higher process efficiency. However, the main disadvantage of MW drying system is the high capital cost, which is reported to be almost double compared to the conventional process (Kumar and Karim 2019, Kumar et al. 2018). The hybrid drying methods, which involve combination of various drying technologies, deserve attention to optimize the energy efficiency, product quality, drying time, and investment & operation cost for food drying in developing countries.

This study aims to present a comprehensive review on different renewable energy based sustainable drying technologies and their utilization suitably applicable in developing countries. Moreover, to reduce the drying time and spoilage, and improve the product quality, different types of hybrid drying systems based on renewable energy are presented and their potentials are discussed.

2. Classification of existing drying technologies

An extensive classification of food drying technologies based on various criteria and thermal properties can be found in Mujumdar (2015). Based on the energy sources, drying technologies can be categorized into traditional (i.e., fossil fuel driven), renewable, electrical, and dielectric drying. Dielectric drying includes microwave and radio frequency drying, which heat the food volumetrically using high-frequency electric fields (Jiang et al. 2016). Furthermore, they can be combined to utilize the advantages and offset the disadvantages of the individual drying technologies. A detailed classification of drying technologies based on energy sources is presented in Figure 2.

Fossil fuel based traditional drying systems have long history since the ancient period. Being diminishing and polluting to environment in nature, fossil fuel based traditional drying systems (Lamidi et al. 2019) need replacement with efficient and renewable energy based drying systems. Being intermittent in nature, it is imperative and challenging task to develop an efficient and acceptable solar dryer suitable for specific agro-products. Availability of geothermal resource is always the precondition of geothermal drying. Geothermal energy has been used to dry fish, olive leave, tomato, etc. in Indonesia, Turkey and Greece (Baksir et al. 2019; Helvaci et al. 2019; Kostoglou, Chrysafis, and Andritsos 2013).The large quantity of harvest residue provide abundant energy source for agricultural drying in the rural area of developing countries (Nalawade and Panwar 2019). However, the high initial moisture of the residue requires preheating before combustion, which is usually energy intensive (Verma et al. 2017). Heat pump assisted drying system suffers from low energy efficiency at the drying stage of low moisture content. Additionally, it requires high capital and maintenance cost (Minea 2013c). However, heat pump system performance and energy efficiency can be improved by employing energy recovery in these drying systems. Dielectric drying was proven to significantly increase the drying rate, while combination with other types of drying can improve product quality and minimize energy consumption (Rahman et al. 2018;Talens, Castro-Giraldez, and Fito 2016).

3. Drying technologies based on sustainable energy sources

Drying of food materials consumes large amount of energy as latent heat to evaporate moisture. The traditional convective drying is time consuming because of the moisture (basically bound water) transfer barrier at the falling rate period (Kumar, Millar, and Karim 2015), which is also very energy-intensive, and hence, often difficult to balance between the energy consumption, drying time and product quality (Mahiuddin et al. 2018). Drying systems consume up to 25% of energy utilized in the food processing industry, which has massive impact on today's environmental sustainability (Mahiuddin et al. 2020). Therefore, developing an energy efficient food drying systems is the key challenge to ensure environmental sustainability (Mahiuddin, Khan, Kumar, et al. 2018). Solar energy is the universally available and most popular renewable energy source. However, other renewable sources, such as, geothermal and biomass have great potential too to be used for food drying (Ibrahim et al. 2009; Kostoglou, Chrysafis, and Andritsos 2013; Yi et al. 2020). The different drying technologies with sustainable energy sources are discussed below.

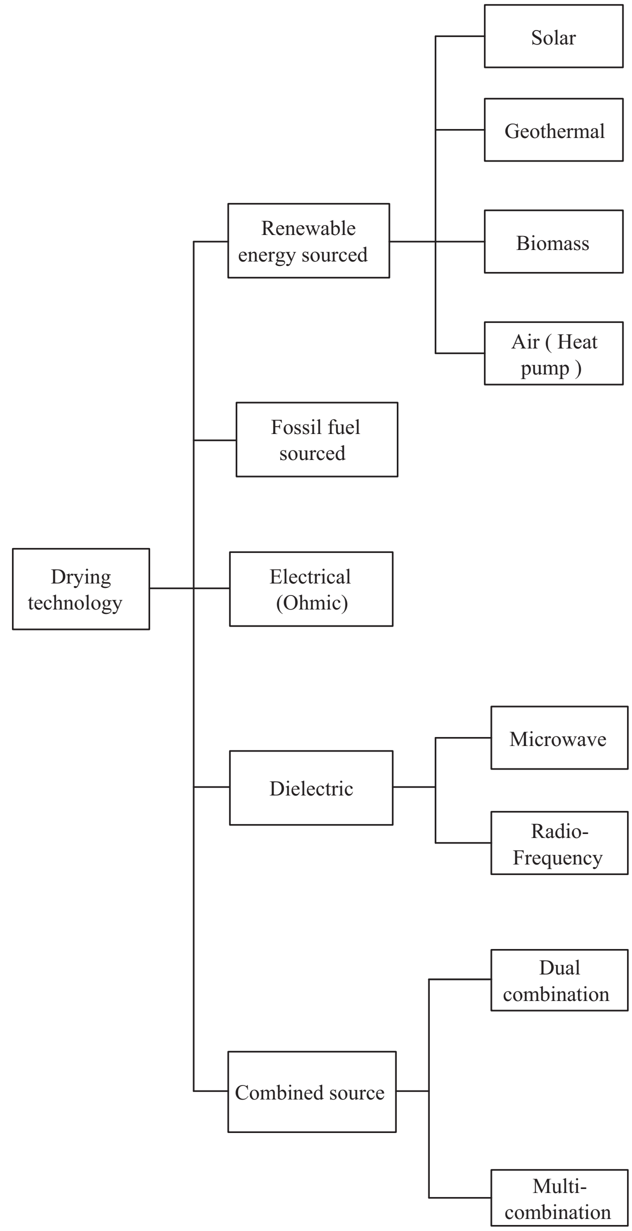

Figure 2. Classification of drying technologies based on energy sources.

3.1. Improved solar drying using thermal energy storage (TES)

The solar dryers with acceptable cost and efficiency are attractive options to replace the open-air sun drying for the

Table 1. Critical characteristics of PCMs.

Storage medium		Heat of fusion (kJ/kg)	Chemical characteristics	Capital cost (USD/kW)
Organic	Paraffin	190–260	nontoxic, flammable	6000–15000
	Non-paraffin (fatty acids)	130–250	Mildly corrosive, highly flammable	Salt
Inorganic	Salt hydrate, metallic	100–200	Corrosive	hydrate < eutectic < paraffin < non-
combination of organic and/ or inorganic	Eutectic	100–230	Dependant on composition	paraffin

farmers of the developing countries. One of the major disadvantages of solar drying is the intermittency of the solar radiation and unavailability of the radiation during night and on rainy days (Masud et al. 2020). The uninterrupted operation of solar drying system is extremely important to ensure a minimum quality deterioration from the micro-organism level. Hybrid solar dryer with back up source or heat storage supplies required energy at the nighttime or cloudy weather (Rahman, Joardder, et al. 2018). Addition of efficient thermal storage system is considered as more economical compared with that of adding supplemental heating equipment based on traditional fossil energy sources.

There are different types of TES in the current engineering applications, namely sensible thermal, latent thermal and thermal-chemical. Thermal-chemical energy storage is still at the development stage. Both of sensible and latent thermal storages are mature and popular in commercial applications. The latent thermal storage is based on Phase Change Material (PCM), which melts releasing latent heat, and solidifies absorbing latent heat cyclically.

3.1.1. Solar drying system with phase change material (PCM) based thermal storage

PCM based thermal energy storage alternatively stores and releases large amount of heat through changing its phases. Due to their unique advantages, researchers attempted to use PCM in diverse thermal applications, including refrigeration and air conditioning (Khan, Afroz, and Karim 2017), building heating, and food drying systems (Abujas et al. 2016).

Selection of PCM is important for the solar dryer application. The PCMs can be categorized into organic, inorganic and eutectic, as shown in Table 1 (Dincer and Ezan 2018). A eutectic based PCM a mixture of two or more components which usually do not interact to form a new chemical compound and possesses a lower melting point than either of the components. Among major required characteristics of the storage substance, the thermo-physical stability in case of frequent cycling is considered critical. Other essential characteristics are the volumetric heat capacity, non-toxicity, and heat transfer rate. Besides energy, cost is also another particular significance for the dryer application in developing countries (Sharma et al. 2009).

Paraffins are the most commonly used PCMs for active and forced hot-air systems. However, available salt hydrate PCMs, which melt in the range of 35 to 50 °C, suffer from incongruent or semi-congruent melting and segregation problems during freeze-thaw cycling (Lane 2018). Paraffin wax are non-corrosive, as well as physically and chemically stable with good thermal behavior. However, it is flammable, and have low thermal conductivity. These drawbacks can be alleviated by adding high thermal conductivity additives and fire-retardant additives (Bal, Satya, and Naik 2010; Shalaby, Bek, and El-Sebaii 2014). Agarwal and Sarviya (2016) experimentally studied a solar dryer with shell-tube type storage using paraffin wax as heat storage medium. It is reported that such a configuration satisfied the requirement of food drying during off-sun period. Discharging time of latent heat storage is longer than charging time because of the lower heat transfer rate during discharge.

Flat plate collectors are the most popular energy collection unit for solar drying systems. Labed et al. (2016) conducted an experimental study on the performance of solar dryer using flat plate collector (FPC) with double pass, and reported that the best performing FPC reduced 75% of henna drying time compared with traditional ones. Hao et al. (2018) constructed and studied a dual-function hybrid drying system using FPC, and reported maximum heat collecting efficiency in the range of 32.5% to 50.8% under different heat collecting models. The heat loss coefficient was in the range of 2.5 to 6.2 W/(m^2K). A conceptual design of advanced geothermal PCM solar collector dryer (PA-FPSC) was proposed by Ananno et al. 2020. Compared to conventional flat plate solar collector, this novel renewable energy-based hybrid dryer reported 20.5% higher efficiency. The combination of geothermal and solar energy together with PCM storage facilitated the dryer to operate up to 20 hours per day (Ananno et al. 2020).

One of the major disadvantages of solar air collectors is the low heat transfer coefficient compared to water collectors. Amount of heat extracted from collector absorber can be increased by increasing the heat transfer area in the form of fins (Mahmood, Aldabbagh, and Egelioglu 2015; Naphon 2005; Yeh and Lin 1996). Addition of fins in the air duct also facilitates turbulence and further improves the performance of flat plate solar collectors. Fudholi and Sopian (2019) further improved the performance of the finned solar collector by integrating with a fluidized bed and heat pump. V-corrugated absorbers plates also increases the heat transfer area and, so, the heat transfer rate (Karim and Hawlader 2006b). Due to multiple reflections within the grooves, V-shaped absorbers also increases the solar absorption. It has been shown that V-groove collector is 12% higher efficient compared to its flat plate counterparts. It was also reported that the thermal efficiency is highly dependent on flow rate as the efficiency was increased from 41% at flow rate of 0.01 kg/m^2s to 71% at 0.054 kg/m^2s (Karim and Hawlader 2006a).

V-corrugated solar air collectors integrated with PCM based thermal energy storage achieved 15% to 21.3% higher

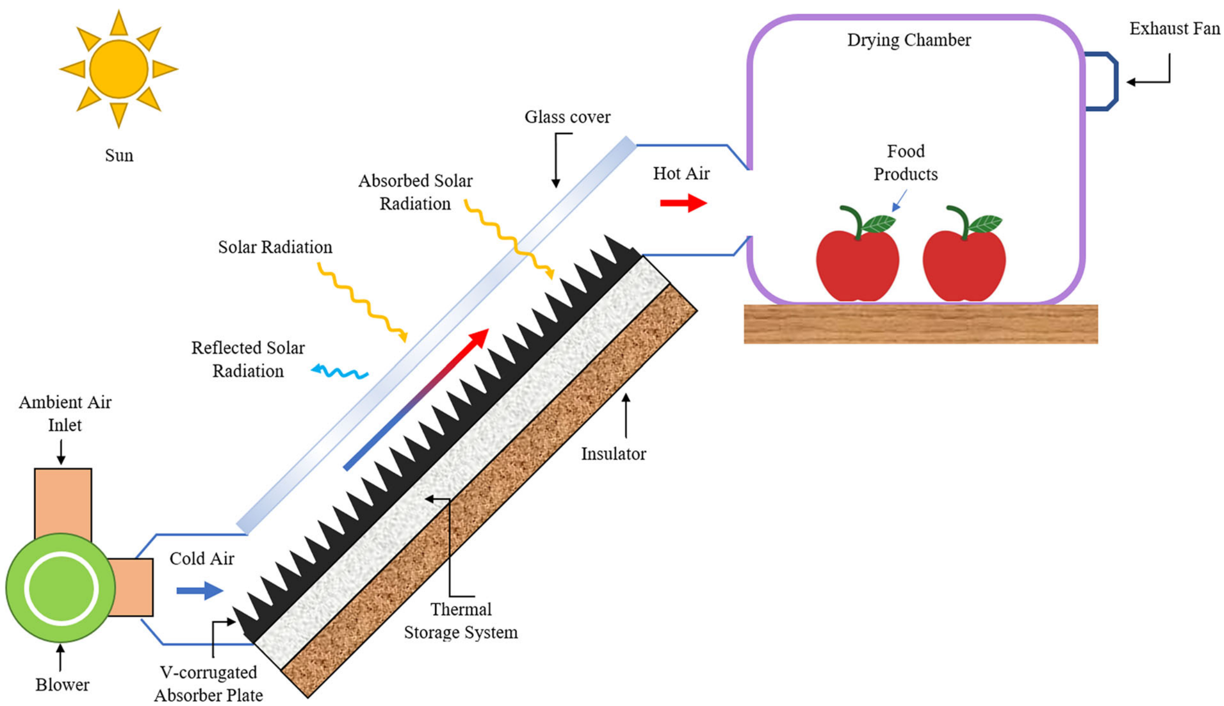

Figure 3. Schematic of improved dryer equipped with V-groove solar air heater and PCM thermal storage (Masud et al. 2020).

efficiency compared to collectors without thermal storage (Kabeel et al. 2016). An advanced solar dryer integrated with PCM thermal storage and V-groove air collector is presented in Figure 3. The PCM material is built in between the back insulation and the V-groove absorber plate of the solar collector. During the peak hours, the thermal storage absorbs excessive heat and release it on demand. With this double enhancement, a prolonged period of drying for the food material can be achieved, which will make the dryer more efficient and the drying product more acceptable.

Deep-bed dryer is typically used for the energy-intensive batch drying of agricultural products. Chauhan, Choudhury, and Garg (1996) used a finite difference approach to simulate deep-bed coriander dryer integrated with solar air collector. The capacity of the dryer was about half ton/batch, and the simulation results showed that the system requires 18 sunshine hours and 13 off sunshine hours to dry a single batch. Without thermal storage, the dryer required 27 cumulative sunshine hours (3 days of sunshine) to dry the same amount of coriander.

3.1.2. Solar dryer with pebble-bed TES

Rock or pebble beds are popular storage unit among various packed beds to store solar energy due to their high volumetric capacity, high heat transfer coefficient, low porosity, low pressure drop through the bed, and low cost of storage material and container. Figure 4 shows a solar dryer equipped with pebble-bed TES. Many researchers attempted to develop solar drying with integrated rock bed thermal storage system. Ayyappan, Mayilsamy, and Sreenarayanan (2016) studied a solar greenhouse coconut dryer utilizing three different heat storage medium and compared their performances, and reported the efficiency for rock-bed was the highest (11.65%) compared to those of concrete (9.5%) and the sand (11%). The properties of different types of rocks are presented in Table 2 (Dincer and Ezan 2018).

Asiedu et al. (Ayensu and Asiedu-Bondzie 1986) used a rock-bed storage solar dryer to dry cassava chips, fish and pepper, and determined the drying characteristics of these products. They reported that compared to open sun drying, their dryer halved the drying time. Tiwari, Singh, and Bhatia (1994) also used rock-bed thermal storage dryer to dry wheat, and reported that the rock-bed storage tank needed 2 hours to reach the steady-state condition.

3.2. Geothermal heating based drying

Geothermal energy utilization can be classified as near ground and deep underground by a conceptual boundary, and the deep geothermal is further classified as high enthalpy and low enthalpy reservoirs (Stober and Bucher 2013). Geothermal resources with low enthalpy at the temperature below 150 °C are suitable for drying of fruits and vegetables (Muffler and Cataldi 1978). Heat is extracted in the form of steam or hot water from geothermal wells. The amount of waste-heat from geothermal power plants is huge, and can be effectively utilized in geothermal drying (Vasquez, Bernardo, and Cornelio 1992). Food drying using geothermal energy has very low operational cost (Arason 2003). Many developing countries, including Bangladesh, India, Chile, Paraguay, Peru and Ethiopia are located near to the plate boundaries, and therefore, are rich in geothermal resources (Gupta and Roy 2006). Therefore, low cost geothermal energy would be an excellent source of sustainable drying technologies in the developing countries situated in the global plate boundaries.

The schematic of a geothermal food dryer is presented in Figure 5. As can be seen in the figure, underground hot

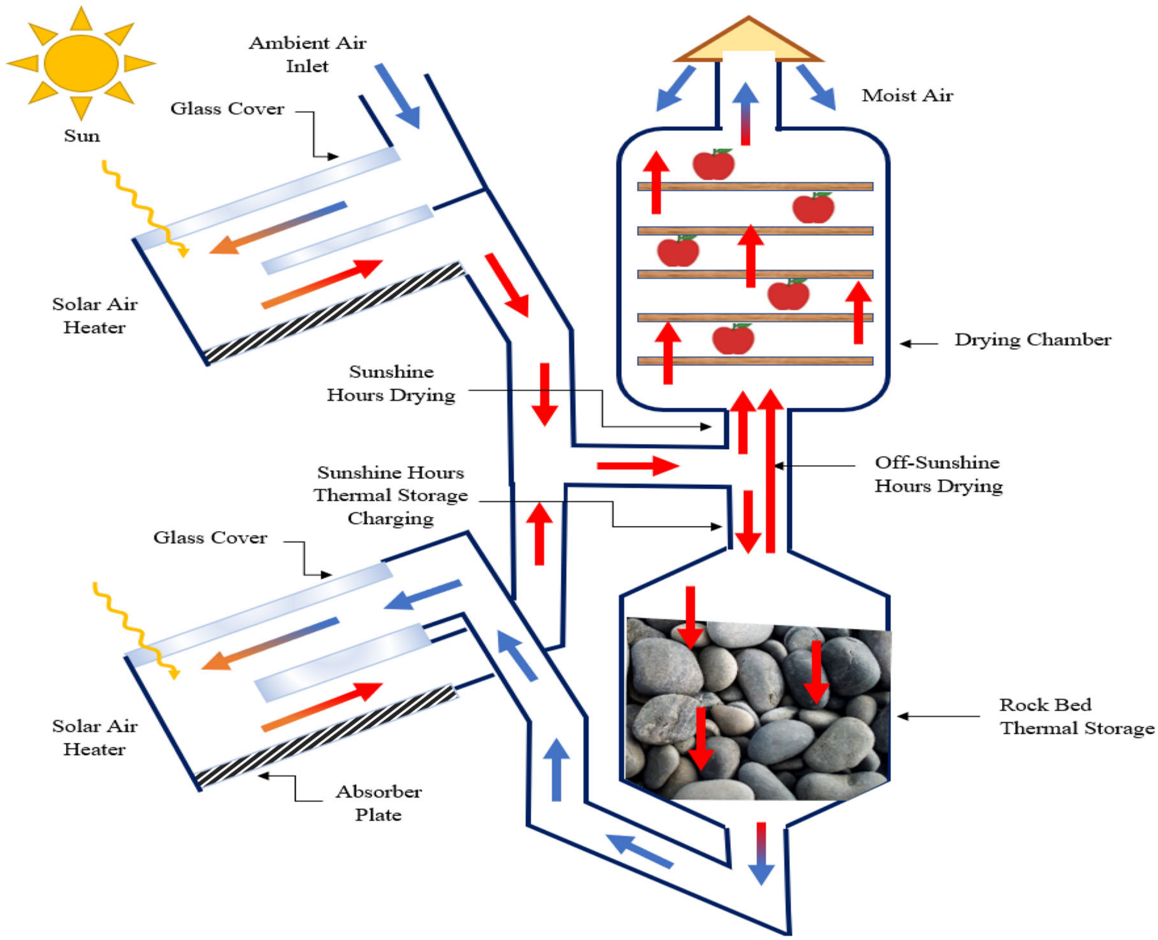

Figure 4. Solar dryer with rock bed storage.

Table 2. Critical characteristics of rock-bed TES candidates for thermal storage.

Storage medium	Temperature range (°C)	Volumetric heat capacity(kJ/m^{3}K)	Density (kg/m^3)	Thermal conductivity (W/mK)
Limestone	Up to 160	1842	2697	2.82 ± 0.06
Helvetic siliceous Limestone	Up to 160	1857	2776	3.60 ± 0.21
Calcareous sandstone	Up to 160	1735	2661	4.36 ± 0.15
Gabbro	Up to 160	1872	2911	2.05 ± 0.08
Quartzite	Up to 160	1634	2615	5.39 ± 0.07

water is pumped through a heat exchanger to heat the air as the drying medium. The heated air is then passed through the trays in the drying chamber.

Lund and Rangel (1995) experimentally investigated a multi-stacked-tray geothermal dryer for fruits drying. The capacity of the dryer was 1 ton per cycle and drying temperature was 60 °C. They reported that fruit samples were dried from 80% (wb) moisture content to 20% (wb) in 24 hours. They also used recovered cascading heat from a geothermal stream to dry tobacco and maize (Mangi 2012). Other types of dryers, including cabinet dryer, convective dryer, tube-bank exchanger dryer, conveyor dryer and rack tunnel dryer are also can be used with geothermal energy (Popovska-Vasilevska 2003).

Hirunlabh, Thiebrat, and Khedari (2007) reported the results of drying of chilies and garlic in a large size cabinet dryer (capacity of 450 kg of chili or 220 kg of garlic). Hot water from a geothermal source circulated through the tubes of a heat exchanger, and air was flowed at a rate 1 kg/second around the tubes. The temperatures of the drying air were 70 °C for the chili and 50 °C for the garlic respectively. Abdullah et al. (2010) reported a tube-bank exchanger dryer project in West Java, Indonesia. The configuration utilized geothermal steam of 160 °C to dry grain and beans.

A geothermal convective dryer of the capacity of 10 tons/hr was built for drying rice from the moisture content of 20% (wb) to 14% (wb) (Van Nguyen et al. 2015). The temperature of geothermal water at the inlet of water-air heat exchanger (WAHX) was 75 °C. The temperature inside the dryer was kept below 40 °C to minimize the rice cracking. The dryer was demonstrated to have competitive advantage over fossil fuel based industrial dryers (Popovski et al. 1992). Lund (2012) developed an industrial-scale geothermal drying system for onion and garlic drying in western Nevada, the USA. This large system had the hourly capacity of 3000–4300 kg of onions, and was able to dry onions from moisture content of 85% to 4% (wb) in 24 hours. In geothermal drying, the drying temperature can be adjusted to as

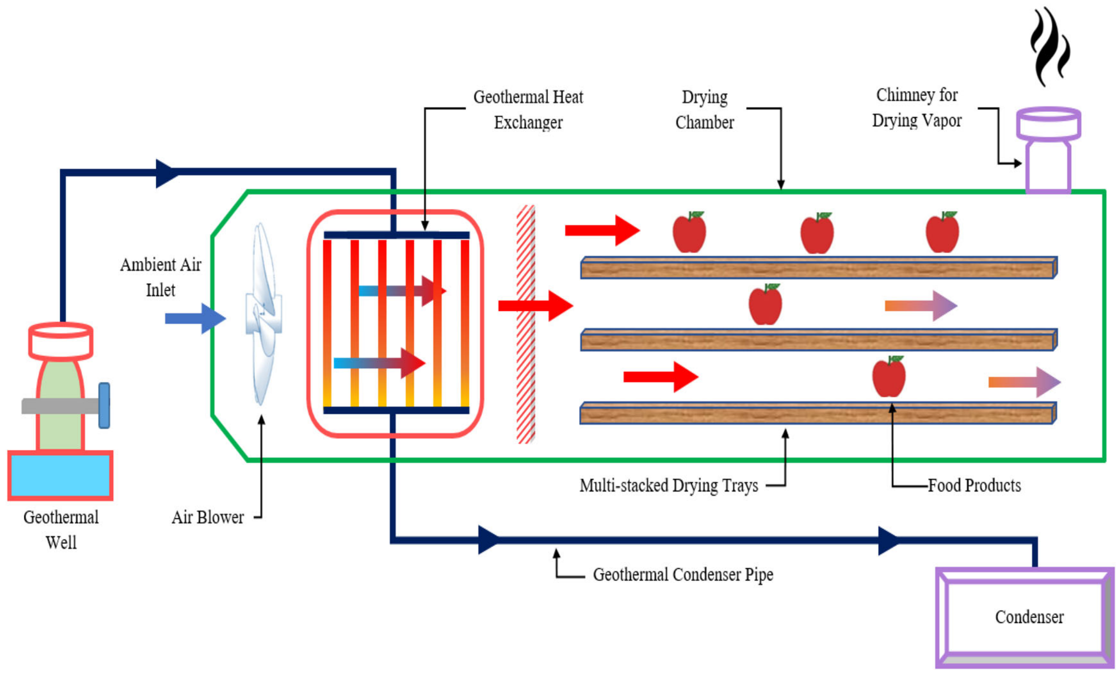

Figure 5. Schematic of multi-stacked tray geothermal dryer.

high as 90 °C and a moderate temperature of 50–60 °C based on the requirements of the products to be dried (Abdullah and Gunadnya 2010).

Rack-tunnel type geothermal dryers are large scale fish dryers with is a multi-stacked tray. In order to develop natural draft and continuous air circulation throughout the dryer, chimneys are generally installed (Van Nguyen et al. 2015). The capacity of these dryers usually ranges from 2000 to 4000 tons. A two stage concept of drying is adopted to reduce the moisture of fish from 80% to 15% (wb) after two-stages drying (Arason 2003). The feed industries extensively use this drying method (Björnsson 2006).

Since, the major field of geothermal energy is electricity production, dying can be integrated together to achieve an economical application. Ambriz-Diaz et al. (2017) presented a cascading geothermal plant for integrated ice-making and agro-products (avocado, tomato and chili) drying. With the cascading, the economics of drying was improved greatly, and especially the payback period of tomato drying was reported to be one year.

It can be seen that diverse types of geothermal dryers can be used for variety of products at different drying conditions. These dyers are particularly suitable for large dryers as demonstrated above. As developing countries have abundant source of geothermal energy, these dryers can be attractive in those countries.

3.3. Biomass based drying system

Biomass energy has been used for centuries as renewable source of heat energy for drying purposes. Hot air is produced from biomass combustion and circulated through the dryer. However, low efficiency is the major concern for the conventional dryer based on biomass as lot of energy is wasted mostly due to the poor design of these dryers. Advanced design with minimum heat loss, better heat and mass transfer rate and good product quality may overcome the limitations of traditional biomass dryers. Continuous direct-heat rotary dryer, flash dryer and fluidized bed dryer are some of the suggested improved biomass dryers (Isaksson, Åsblad, and Berntsson 2013; Liu et al. 2015).

Design of an efficient fluidized bed dryer is challenging as crust formation and improper transportation of the samples due to plug-flow characteristics may reduce the performance. Higher air flow in the feeding section and vibration of the bed can help in reducing these problems. However, the vibrating equipment should be mounted outside the dryer in order to avoid exposure to high temperature (Van't Land 2011). Schematic diagram of a continuous fluidized bed improved dryer based on biomass fuel is presented in Figure 6, where two major components of the improved dryer are a biomass combustion chamber and a continuous feeding mechanism.

Biomass dryer can also be integrated with solar collectors. Hamdani, Rizal, and Muhammad (2018) investigated a solar assisted biomass fish dryer. In their experiments, about 100 kg of fish was dried in 15 hours. The dryer was economically viable as the payback period was just 2.6 years. It is evident that solar assisted biomass dryers can be operated continuously and economically and can back up each other.

4. Heat pump-based hybrid drying

Heat pumps (HP) save energy by making use of the heat energy from surrounding environment. Meanwhile, air based heat pump dryer is the predominating form in the drying application as the air can be used directly as drying medium (Dinçer and Zamfirescu 2016). Most of heat loss in air convective dryers comes from the energy remained in the moist air exhausted from the dryer and the inadequate thermal

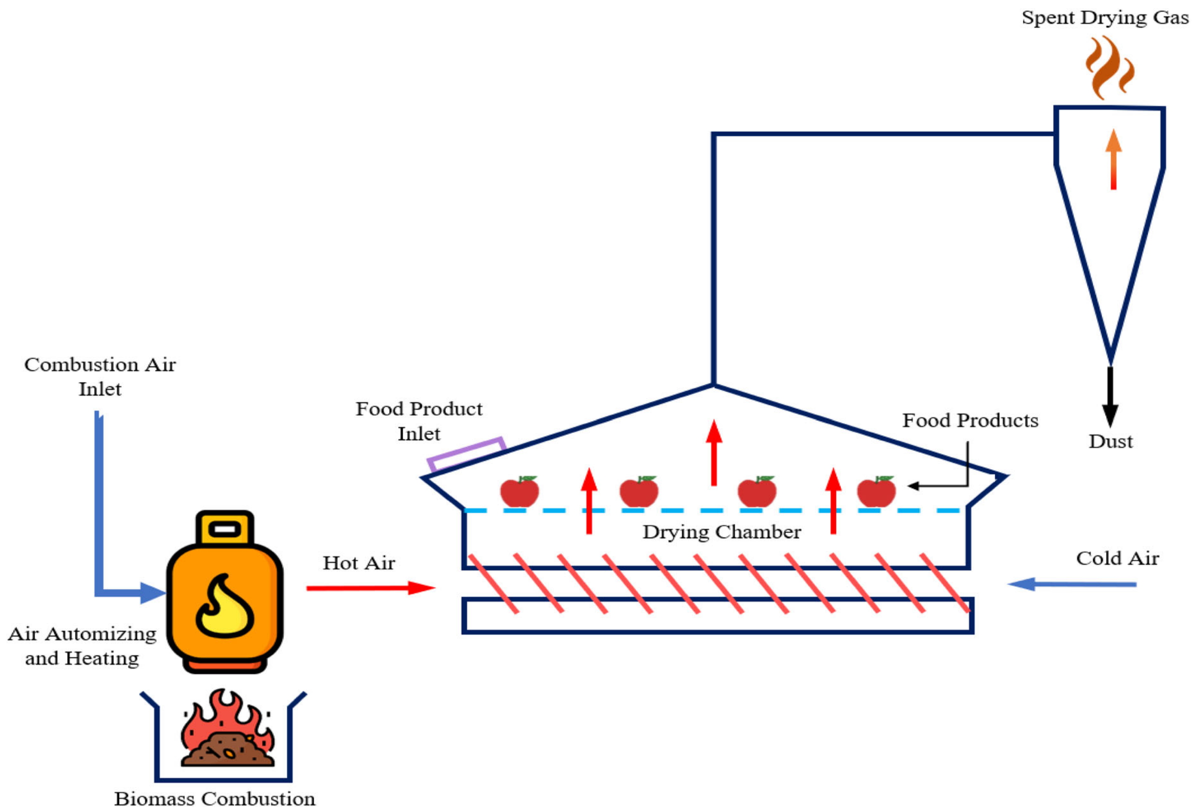

Figure 6. Fluidized bed dryer using biomass as energy source.

insulation in the drying chamber. As heat is recovered in heat pump-convective integrated dryers, these dryers have the potential to save up to 50% energy compared to convective dryers (Minea 2018). On top of energy saving, heat pump dryers also improves the quality of dried food as demonstrated by Hou et al. (2020) through drying of jujube. Ismaeel and Yumrutaş (2020) found that heat pump dryer significantly improved the energy-efficiency as compared to the conventional drying system. Any convective dryers can be integrated with heat pump except those require large amount of drying air, such as spray or flash dryers (Alves and Strommen 1996).

Heat pump dryer is very effective in the developing countries with high humidity climate, where the ago-product spoilage rate increases sharply during the rainy season since it can adequately control the humidity during drying process to effectively remedy this crisis.

Due to these advantages, many researchers investigated various aspects of heat pump dryers, and continuously advanced the heat-pump drying research. Some of the notable research works and their key achievements in heat pump drying are presented in Table 3.

The efficiency of a heat pump dryer can be improved by integrating with different other heating methods, such as, solar heating and microwave heating. These types of advanced food drying systems can be defined as hybrid drying technologies as discussed below.

4.1. Solar assisted PCM integrated heat pump dryers

Solar thermal storage system using PCM can significantly reduce the drying cost, and make the hybrid heat pump drying more flexible. The hybrid system with its stored energy for off sunshine hours results in higher efficiency. An advanced design of solar-assisted heat pump dryer integrated with PCM thermal storage is presented in Figure 7.

These dryers were demonstrated to be energy efficient and produce better quality of products. However, despite its huge potential, research on this field is still inadequate. Qiu et al. (2016) developed a solar-assisted heat pump dryer with heat recovery and water thermal storage. They reported an impressive energy saving of 40.53%, 53.39% and 58.17% compared with parallel solar heat pump drying, hot air drying with open damper, and hot air drying with half-open damper respectively. Payback period was 2–6 years depending on the product to be dried.

4.2. Heat pump-based microwave convective drying

Although heat pump assisted drying is a promising technology that may recover 90–95% of the heat absorbed by the wet material, this drying approach is a very slow process (Patel and Kar 2012). In this case, microwave technology can be applied to accelerate the drying rate and drastically reduce the drying time by around 80% (Kumar, Joardder, Farrell, Millar, et al. 2016). In case of microwave (MW) drying, electromagnetic energy propagates through the free space and heats up the materials volumetrically, which eventually accelerates the moisture transfer (Khan et al. 2020). However, continuous MW application causes uneven temperature distribution, which results in deterioration of the product quality. Application of MW energy intermittently with convective drying (IMCD) can overcome these

Table 3. Previous studies on heat pump drying.

Application	Key achievements	References
Banana	The dependence of moisture diffusivity on temperature was described by an Arrhenius-type equation and the activation energy was found to be −51.45 kJ/mol.	Tunckal and Doymaz (2020)
Banana and potato chips	Effects of drying time on various performances and drying kinetic parameters are presented.	Singh, Sarkar, and Sahoo (2020)
Wheat	Annual energy saving is 21.4% in comparison with the same system without using heat recovery unit for the same input data.	Singh, Sarkar, and Sahoo (2020)
Jujube	Jujube slices dried by heat pump drying showed significantly lower color difference and shrinkage ratio than hot air drying.	Hou et al. (2020)
Wheat	It is observed that all performance parameters including COP and energy fraction for the load increase gradually from the beginning of drying operation until the fifth year of operation. The system works as a periodic operation from fifth year onwards.	Ismaeel and Yumrutaş (2020)
Fruit and vegetable	HP drying contributes positively to quality attributes such as microbial safety and vitamin retention	Fayose and Huan (2016)
Grape pomace	HP energy consumption reduced by up to 51% compared to convective dryer; the losses in all bioactive properties were less than the total anthocyanin.	Taşeri et al. (2018)
Grain	Total power consumption reduced by about 10% compared to hot air dryer; rough rice fissuring rate decreased by about 40% compared to conventional dryer	Harchegani et al. (2012)
Squid fillet	HP drying demonstrated the potential for industrial application considering the production cost and product quality	Deng et al. (2015)
Macadamia nut	Multistage HP drying under modified atmosphere (N_2) showed benefits in the preservation of natural quality of macadamia nuts	Devahastin et al. (2013)
Banana	Ester compounds were found to be the most affected, with losses varying from 25 to 87% for banana drying using low temperature HP; high molecular weight compounds, such as elemicine and eugenol, were not affected significantly	Saha et al. (2018)
Agricultural and marine products	A new hybrid drying technology was developed, which reduced the environmental impact	Chou and Chua (2001)
Pepper	Green sweet pepper was dried using a heat pump dryer at 35°C and achieved a good quality product	Pal, Khan, and Mohanty (2008)
Mushroom	Mushrooms were dried using a solar assisted heat pump dryer at 45°C drying air temperature and 310 kg/h mass flow rate and high-quality product was achieved. The COP of the heat pump was higher than ordinary HP.	Sevik et al. (2013)
Cocoa bean	Up to 73% cocoa polyphenols was retained as compared to freeze drying.	Hii, Law, and Suzannah (2012)
Yacon slice	Yacon was dried using a heat pump dryer and it was found that drying temperature and air velocity had minimum impact ($p > 0.05$) on quality (i.e. total color difference and shrinkage rate) of the dried products	Shi, Zheng, and Zhao (2013)

problems (Kumar, Joardder, Farrell, Millar, et al. 2018). Therefore, an integrated IMCD and heat pump dryer with an appropriate intermittency of MW has the potential to be an energy and time efficient drying system (Kumar, Joardder, Farrell, and Karim 2016, 2018).

Researchers have studied the food drying rate and quality parameters of microwave convective drying extensively. Bhattacharya, Srivastav, and Mishra (2015) studied the microwave-assisted convective drying of mushroom, and found that the drying time of mushroom was reduced by 50% compared to convective drying. Sadeghi, Mirzabeigi Kesbi, and Mireei (2013) investigated microwave-assisted convective drying for lemon slice drying. It was reported that the quality parameters, including the color changes, chroma, and rehydration capacity of the food stuffs were improved compared to those produced in convective drying. Mujumdar and Xiao (2019) studied drying of apple slices using intermittent microwave- assisted convective dryer, and reported higher color change, higher phenol content, lower bulk density and higher rehydration rate compared to those of continuous microwave-assisted convective drying.

4.3. Heat pump based solar-microwave drying

Solar drying is one of the most promising applications of solar thermal energy (Prakash and Kumar 2017). Integration of solar drying with other advanced drying methods can significantly improve the performance. For example, heat pump-based microwave convective drying (HPMCD), utilizing the advantages of low cost solar convective heat, energy recovery of heat pump drying, and short dry time and good quality of microwave drying, has the potential to overcome the current problems for food drying.

By the authors' best knowledge, currently, there is no literature on the HPMCD, and very limited studies on combined heat pump and MW drying. Jia, Clements, and Jolly (1993) developed a MW assisted heat pump dryer, and reported that heat pump assisted microwave drying has the potential to be the best dryer both in terms of energy efficiency and product quality. Shi, Zheng, and Zhao (2014) investigated the effects of drying temperature, air velocity, moisture content and microwave power on the average drying rate (DR), specific moisture evaporation rate (SMER), total color difference (ΔE), rehydration ratio (RR) and

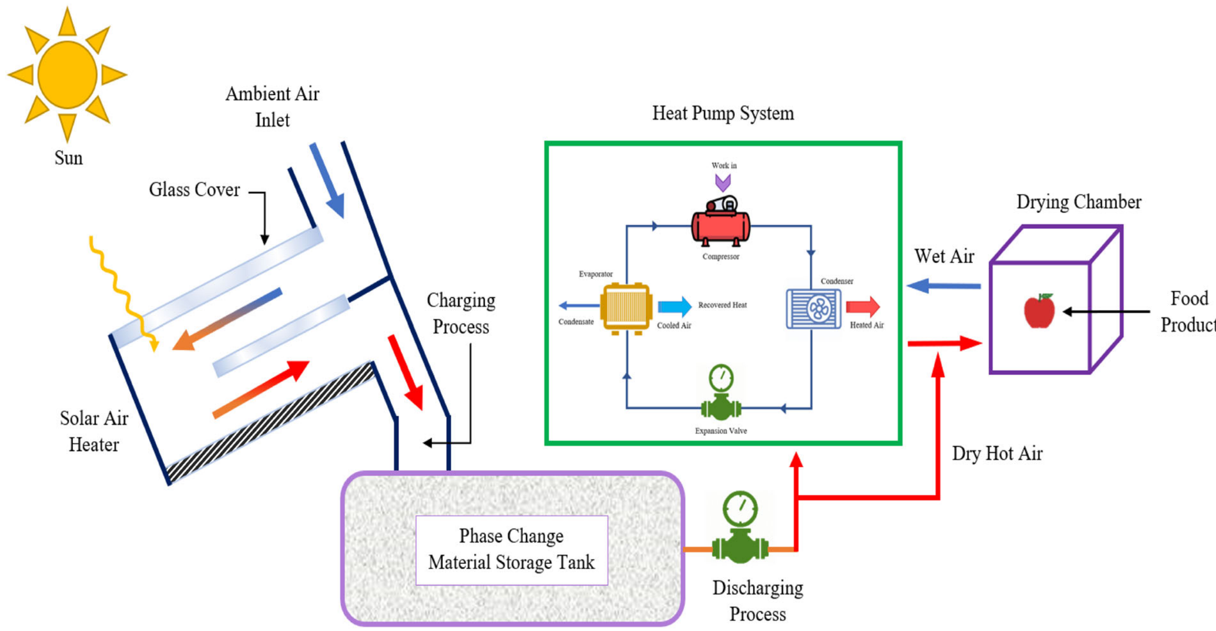

Figure 7. Advanced solar-assisted heat pump dryer with PCM thermal storage.

shrinkage ratio (SR) of yacon dried by combined heat pump and MW methods. Their study determined the optimum drying conditions.

A practical and economical hybrid drying system need considerate design and optimization to utilize the advantages and overcome the shortcomings of the individual components. MW energy should be applied in the falling-rate period of heat pump drying when the moisture content is generally as low as 20%–25% and the air moisture changes little (Araszkiewicz et al. 2004; Minea 2013a).

The high total costs and complexity of these systems are always barriers to the access of large-scale commercial applications, and profits obtained from the applications need to be compared with the investments to study the feasibility.

5. Comparison of various drying technologies

An energy efficient dryer with multifunctional abilities, which can successfully dry any kind of food materials at any drying parameters, does not exist yet. Drying technology should be selected based on the requirements, such as, characteristics of the product to be dried, desired product quality, and installation, maintenance and operating costs of the dryer. Fito, Amparo, and Martin (2004) suggested that MW drying can be economically more attractive for cases where low cost raw materials can be converted to high end product after drying. However, a comprehensive study is needed to take all related factors into consideration. Table 4 shows the major technical characteristics (e.g. drying time and quality), as well as, economic factors of the related renewable energy based drying technologies with comparison to common convective and microwave ones (Hii et al. 2012; Prakash and Kumar 2017; Sanio and Schmidt 1990).

Renewable energy-based dryers generally require high capital costs, but low operational costs. Therefore, it is critical to conduct economic analysis, and determine the payback period from fuel savings.

6. Feasibility of sustainable drying in the developing countries

Large-scale adoption of the advanced drying technologies is a challenging task in developing countries. When a real project is proposed, many factors (i.e., economic, political, social, and environmental) besides the technological issues must be considered and balanced cautiously, otherwise the project may not be succeeded. The major issues that need to be considered are the availability and distribution of renewable energy resources, and government policies and incentives as discussed below.

6.1. Distribution of renewable energy resources

Renewable energy projects are site-specific and determined by the indigenous resources. The global solar irradiance is good to excellent (1800–2300 kWh/m^2) in the regions between 45^0 south and 45^0 north, which covers Middle East, parts of the United States, Africa, most of Latin America, Australia, Pakistan, most of India, parts of China and parts of Southeast Asia (IEA 2011). Most developing countries are located in those regions and thus is favorably positioned to utilize solar dryers economically. Unlike the globally spread solar energy and the biomass resources backed with forestry and agricultural residues, geothermal resource is mainly concentrated around the Pacific Plate which includes huge territory from Indonesia, the Philippines and Japan to Alaska, Central America and Mexico. Numerous developing countries with geothermal resource are scattered in Africa, Latin America and Caribbean, Asia and Europe, such as Kenya, Ethiopia, Egypt, Chile, Peru, Ecuador, India, Iran, Philippines, Thailand and Turkey (Van Nguyen et al. 2015).

Table 4. Comparison of the renewable sourced and traditional drying technologies.

Classification	Characteristics	Food stuff to be dried	Economic	Drying time	Drying quality
Convective	Most common, long drying time, easy to develop crust on the surface	Wide variety of crops	Relatively low	1–6 hr	Low to medium
Microwave	Improve drying efficiency, easy to overheat in the final stage, normally combine with other drying methods	Cash crops	High, almost twice the hot air convective	30 s–5 min	Medium to high
Heat pump	Heat recovery from exhaust, improved product quality by delicate control	Cash crops, heat sensitive	High investment and maintenance cost	5–60 min	Low to medium
HPMCD	Combination of heat pump, microwave and (solar) convective drying to utilize advantages of various technologies. Simulation and further research pending	Cash crops, heat sensitive	Potential to achieve the cost effectiveness due to the use of solar heat	30 s–5 min	High
Solar	Abundant and accessible resource, performance enhanced with V-corrugated plate and heat storage (PCM or rock-bed)	Wide variety of crops	Viable if extra capital cost can be balanced by fuel saving, or compensated	6–10+ hr	Medium
Geothermal	Depend on local resource, utilize geothermal resource below 150 °C	Ordinary crops	by government	10+ hrs	Low to medium
Biomass	Abundant and accessible resource, performance can be enhanced by advanced mass & heat transfer mechanism such as continuous fluid-bed	Ordinary crops		30–60 min	Low

Therefore, many developing countries can economically use geothermal energy for drying applications.

6.2. Governmental policies and incentives

Energy and environment have been widely recognized as the most important global issues in the 21st century. Due to high energy consumption in the food drying process, the improved and efficiency drying technologies, which adopts renewable energy, have the potential to draw government's attention. However, the high capital cost of renewable energy drying application is the main barrier against successful implementation of these systems (Masud et al. 2020). Compared with the developed countries, most farmers and small investors in the developing countries have lack of financial resources and comprehensive supporting and promoting systems.

Some developing countries, including the major global energy consumers have made long term efforts to achieve sustainability in energy utilization. China plans to reduce the energy intensity by 15% from the period of 2015 to 2020, India seeks to improve building energy efficiency through implementation of different programs, such as National Energy Efficient Fan Program, and Thailand aims to cut the energy intensity by 30% by 2036 compared to 2020 level (Delina 2017).

Those governments need to particularly focus on drying as it is one of the most energy intensive systems of food processing industry, and could be taken the following measures to promote the development of sustainable drying technologies (Wilkins 2010)

- The government should call for awareness among different stake holders in the potential market regarding renewable energy based drying technologies.
- Issue incentives, such as tax & duty reduction to attract the private investors.
- Create friendly business environment, such as supporting infrastructure, regulation, and legislation that will help to minimize the local resource consumption and will protect environment.
- Inquires locals' suggestions to meet the requirements of community.

Among all these measures, the governmental financial subsidies, which can directly reduce the capital cost and make the projects financially feasible, are the major driving forces for the development of sustainable drying technologies in developing countries.

6.3. Current challenges & future direction

It is generally accepted that higher energy efficiency, lower environmental impacts, more use of renewable energy in drying applications, and better-quality products at lower total costs will be the future focus of drying technologies (Minea 2013b). In addition to these, developing countries will also focus on the initial & operation cost. Cost evaluation is site dependent, and varies with different food materials, which makes it a complicated process. Food drying is an interdisciplinary technology involving both food science and thermal engineering knowledge. It remains to be a challenging research and development (R&D) task to achieve better drying efficiency and product quality while maintaining lower investment and running costs.

Since drying is an energy intensive process, great attention need to be paid to the development of energy-efficient drying processes (Chua et al. 2002). However, increased consumer demand for high quality products is making the quality more attractive than the energy efficiency, especially for the high valued agricultural products, such as cash crops, whose favorable sales price can mitigate the burden of the intensive cost (Kumar and Kandpal 2005). Promising hybrid drying technology, such as intermittent microwave convective drying, and heat pump based solar drying with thermal storage thus offer imperative solutions in terms of balancing of both energy efficiency and product quality. These technologies/sources still have much room for improvement; thus, the researchers and engineers can investigate the current bottlenecks for future improvements.

Due to obvious limitations of the individual drying technology, development of combined drying application in the future is predictable. Although numerous studies on various dryers already exist, researchers and engineers are still facing urgent and challenging R&D tasks to develop and optimize the combinations of specific drying technologies and/or energy sources (e.g., solar, heat pump, microwave, etc.). HPMCD has huge potential to achieve the goals, however, is still in the initial step of development, and theoretical study is a good start for its research. Deployment of improved renewable energy drying techniques is not a mere technological issue; rather a systematic and multidisciplinary issues that require technological, economic, political, environmental, and sociological consideration.

7. Conclusion

The nutrition insufficiency in developing countries, as well as large proportion of environmental burden due to the food waste, awaken the interests in utilizing sustainable drying technologies, including solar, geothermal, biomass and heat pump drying. This paper presents a comprehensive review on these sustainable drying technologies. This article also presents the current and past research works in hybrid drying technologies, including heat pump drying combined with PCM, and integrated solar and microwave convective drying. On the basis of the advantages of individual drying technologies, the combined drying technologies deserve particular attention. The under-researched hybrid drying technique HPMCD, which combines HP, MW, and solar convective drying, is a candidate from the promising combined drying technologies. With capability of reducing drying time by up to 90% and better retention of nutrient component, microwave drying deserves an important part of the combined drying system. Considering the complexity and high capital cost of such a project, theoretical study would be a good start for its research. Moreover, it can be said that the solar drying systems with thermal energy storage and integrated heat pump drying is the most promising drying technology in terms of energy efficiency and product quality. Advanced hybrid integrated drying systems, such as solar with microwave, and heat pump with microwave make the drying more cost competent and achieve better product quality.

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