Importance of integrated CFD and product quality modeling of solar dryers for fruits and vegetables: A review

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Abstract: Improper handling of fruits and vegetables causes a significant postharvest loss. Among the postharvest preservation mechanisms, solar dryers are reported as sustainable and suitable preservation systems for fruit and vegetable products. This paper summarizes the recent advances, opportunities, and challenges in solar drying of fruit and vegetable products. Besides, the review discusses the commonly used mathematical models for the evaluation, design, and optimization of solar dryers. The review discusses the factors that affect the performance of solar drying systems concerning drying time, drying rate, and product quality attributes. Short drying time, uniform drying air velocity, temperature, and product moisture distribution in the drying chamber are the critical parameters that are required for an efficient operation of a solar dryer. There is a good prospect in the application of mathematical modeling techniques such as computational fluid dynamics (CFD) in identifying the optimum solar drying conditions and dryer design that can maintain the required quality of the product. CFD has been used extensively in studying the airflow, heat, and mass transfer processes for optimizing the design and operation of different drying systems, similarly different quality models have been applied to evaluate the quality of dried products. However, most CFD studies did not include the quality aspect for dryer performance evaluation or optimization studies. To get the best result, CFD based performance evaluation or optimization studies of the solar dryers should have the capacity to predict the product quality in addition to the airflow, heat, and moisture transfer characteristics.

Keywords: Solar dryer, CFD modeling, Drying, Fruits and vegetables, Postharvest loss, Quality

1. Introduction

Understanding global population growth and anticipating the energy and food demands to come is crucial for sustainable development. According to the United Nations population projection, the world population is expected to reach 8.5 billion in 2030, 9.7 billion in 2050, and 10.9 billion in 2100 with high energy and food demands (United Nations, 2019). Energy and food are the essential driving aspects for the survival of human beings. To sustain the balance between population growth and food supply, food losses during pre-harvesting, post-harvesting, and market chains should be minimized through appropriate technological innovations and advancements. The quantity and quality of agricultural products significantly suffer due to poor preservation mechanisms and processing methods. Post-harvest losses of agricultural products have highly prevailed in many developing countries. Many reports indicated that the postharvest losses of fruits and vegetables in developing countries are nearly 30%-40% (El-Sebaii and Shalaby, 2012). Thus, considering the significant importance of fruits and vegetables in different aspects, especially in the food industry, human health, and national and international market economy, preservation of fruits, vegetables, and other types of agricultural food is very essential for keeping them for a long time without further deterioration in the quality of the products and minimizing the post-harvest losses.

Among food preservation technologies, cold storage is the best way to conserve its nutritional value, however, most cold storage techniques demand low temperatures, which are very challenging to sustain throughout the distribution chain of the products (Sagar and Suresh Kumar, 2010). On the contrary, drying is the most suitable option to preserve fruit and vegetable for a long time and reduced postharvest loss, increase shelf life, preserve its quality attributes, and reduce transport weight and cost. Removing moisture leads to slow down the activity of enzymes, bacteria, yeasts, and molds that deteriorate the quality of products. Table 1 presents the moisture content, drying temperature, and the safe limit of the various agricultural commodities during drying processes (Prakash and Kumar, 2014).

There are different types of drying technologies for fruits and vegetables. Among these, solar drying (Fadhel et al., 2011), sun drying (Akpinar, 2006), vacuum drying (Akbudak and Akbudak, 2013), tray drying (Kadam et al., 2011), fluidized bed drying (Marques et al., 2009), (Mihindukulasuriya and Jayasuriya, 2013), osmotic drying, microwave drying, ohmic drying and combination of thereof (Cenkowski et al., 2004) are the major ones used to preserve vegetables and fruits. There are a lot of factors such as drying conditions, product type, drying efficiency, quality, cost of drying operation, and energy consumption to be considered during the selection of appropriate drying technologies. The development of novel fruit and vegetable drying technologies at low temperature and low energy consumption have been progressively increased which show high product quality. Such novel dryers mainly used osmotic, vacuum, microwave, ultrasound, spray, freeze, and fluidized bed drying techniques.

Table1: Details of moisture content of the various agricultural commodities (Prakash and Kumar, 2014).

Agricultural commodities	Initial moisture content (wb%)	Final moisture content (wb%)	Maximum allowable temperature. (ºC)
Paddy, raw	22-24	11	50
Paddy, parboiled	30-35	13	50
Maize	35	15	60
Wheat	20	16	45
Corn	24	14	50
Rice	24	11	50
Pulse	20-22	9-10	40-60
Oil seed	20-25	7-9	40-60
Green peas	80	5	65
Cauliflower	80	6	65
Carrot	70	5	75
Green beans	70	5	75
Onion	80	4	55
Garlic	80	4	55
Cabbage	80	4	55
Sweet potato	75	7	75
Chilies	80	5	65
Potatoes	75	7	75
Apricot	85	18	65
Apple	80	24	70
Grapes	80	15-20	70
Bananas	80	15	70

Guavas	80	7	65
Okra	80	20	65
Pineapple	80	10	65
Tomatoes	96	10	60
Brinjal	95	6	60

Non-thermal drying process such as pulsed electric, ultrasound, and ultraviolet radiation may cause a temperature change inside the product without generating heat within the product that results in lower quality deterioration of the product due to the low drying temperature as compared to thermal drying process (Raso and Barbosa-Cánovas, 2003). Reduced drying time, increased processing efficiency, and enhanced quality attributes are some of the importance of non-thermal drying processes. However, some advanced drying technologies have their limitations. Khin et al. (2005) indicated that vacuum drying, freeze-drying, osmotic dehydration, and ultrasound are highly costly for large scale drying process, especially in developing countries where technological advancements are limited due to level of income and skilled manpower. There are various sources of energy such as electricity, fossil fuel, natural gas, biomass, and solar energy which can be used for agricultural produce drying, therefore, the aim of this review work comes under the application of solar energy.

Solar energy is a highly attractive and sustainable and renewable source of energy as compared to other fossil fuels that pollute the environment. One of the advantages of solar drying is that it offers highly effective and efficient preservation techniques to reduce postharvest losses, product quality, and balance the shortages in supply during non-production season for the consumers. It is also a more convenient alternative energy for rural societies who are living far from the electric grid. Studies conducted on solar drying have proved that it is a good energy supply alternative in solar drying technologies for the production of high quality dried products (Tunde-Akintunde, 2011).

Most developing countries use traditionally well-known open air-drying method to dry crops. Open sun drying is the cheapest and simplest method of drying of agricultural products such as vegetables, fruits, grains, cereals, tobacco, timber, etc. by spreading them on the ground and mixing regularly until sufficiently dehydrated. However, though open sun drying requires little capital and workforce, it has a huge limitation on the quality of the products (Sahdev, 2014). The limitations of open-air drying is that it requires long drying periods and a large drying space, deterioration of quality by overheating, hostile weather conditions, contamination of fruits from the foreign materials, and infestation by rodents, insects, birds and other animals (Purohit et al., 2006). Moreover, open sun drying may bring structural and physical changes in the product such as shrinkage, case hardening, loss of nutrient and volatiles components, and lower water re-absorption during rehydration (Tiwari, 2016). Due to these limitations, the total loss of vitamin C and beta-Carotene of fruit and vegetables is significantly increased in open sun drying (Kasso and Bekele, 2018, Ndawula et al., 2004, Mulokozi and Svanberg, 2003). To overcome the limitation of open-air drying, the improvement and use of well-designed and controlled solar dryers is very essential. However, during solar drying, some important properties of the fruits and vegetables such as flavor, texture, color, pungency, and nutrients have usually changed. Different reports indicated that the solar drying parameters such as humidity, air velocity, temperature, bulk porosity, and water activity have a significant impact on the quality of the products (Dolinsky et al., 2000, Opara et al., 2009 and Harrison and Andress, 1914).

Previously, different studies have discussed the improvement of the solar drying of fruit and vegetables based on solar dryer classification, drying energy minimization or theoretical and empirical models (Kumar et al., 2016, Tiwari et al., 2016, Fudholi et al., 2010, Fudholi et al., 2015, Onwude et al., 2017, Bennamoun, 2011, Sagar and Suresh Kumar, 2010, Husham Abdulmalek et al., 2018, Lingayat et al., 2020, Mustayen et al., 2014, M. I. Fadhel et al., 2011, Fudholi et al., 2010). The existing solar drying review mainly focused on experimental studies and analyzing the dryer performance. There have also been immense research outputs using CFD based on mass and heat transfer on a micro level. The micro level CFD modeling indicates that the modeling and simulations was conducted on a fruit and vegetable level, not considering the performance of the solar dryer. However, the performance of a solar dryer has a huge effect on drying rate and kinetics, consequently determining the product quality. In this aspect, there is limited information in the literature to show explicitly the importance of CFD modeling and simulation on the performance of solar dryers for fruits and vegetables. However, dried food product quality is determined indirectly through the analysis of an uniform distribution of drying parameters in the solar dryer chamber. The quality of fruit and vegetables is very sensitive to solar drying parameters such as drying temperature, air velocity, and other drying parameters. These parameters can be optimized through rigorous modeling and simulation techniques using the CFD model. The CFD modeling and simulation techniques are extremely important to develop efficient solar dryers, analyze and predict the performance of different kinds of solar drying system that preserve quality of food products. Therefore, the current review puts emphasis on the macro scale (solar drying system) CFD modeling and simulation in the solar drying of agricultural produce rather than the micro scale (CFD modeling only on the fruit and vegetables).
Drying is characterized as a combined multiscale, multiphysics and multiphase problem, which is a very complex process. Therefore, CFD modeling is very essential in this aspect to explicitly describe the drying process. So far, very few works of CFD modeling and simulation of solar dryers have been reported (Romero et al., 2014a, Amanlou and Zomorodian, 2010, Ghaffari and Mehdipour, 2015, Prakash et al., 2016, Sonthikun et al., 2016, Tegenaw et al., 2017, 2019a and 2019b). The aim of this review is to see most recent development, opportunities and challenges in macroscale CFD modelling and simulation of the solar drying of fruits and vegetables focusing on drying time, drying rate, drying uniformity, dryer design and quality attributes. The review will make recommendations on the CFD modelling approach of solar dryers for future researchers.

2. Drying mechanism

Drying is a mass and heat transfer phenomenon that removes moisture from a solid product by passing hot air around it to carry away the released vapor. Moisture pickup continues until the vapor pressure of the product and the environment are equalized (Ekechukwu and Norton, 1999). Therefore, the rates of moisture absorption from the environment and desorption from the product to the environment is known as the equilibrium moisture content. Under ambient atmospheric conditions, there is a high relative humidity in the environment and the drying process is very slow indicating a high equilibrium moisture content for safe storage. Thus, the objective of any type of dryer is to provide more heat to the product to maximize the vapor pressure of the product moisture and reducing greatly the relative humidity of the drying air (Ekechukwu and Norton, 1999, Ekechukwu, 1999, Nasri and Belhamri, 2018). There are different mechanisms to pick up moisture from the product such as capillary action surfaces and liquid diffusion within fruits and vegetables (Erbay and Icier, 2010). However, diffusion is the dominant mechanism to remove moisture from fruits and vegetables (Hashim et al., 2014). The change of the wet bulb temperature, moisture ratio, and drying rate versus time is portrayed in Fig. 1. When the temperature of the fruit and vegetable increases, the drying rate also increases (A to B) until the surface temperature sustains equilibrium (B to C). The falling rate period is highly governed through diffusion in which most vegetables and fruits are usually dried within.

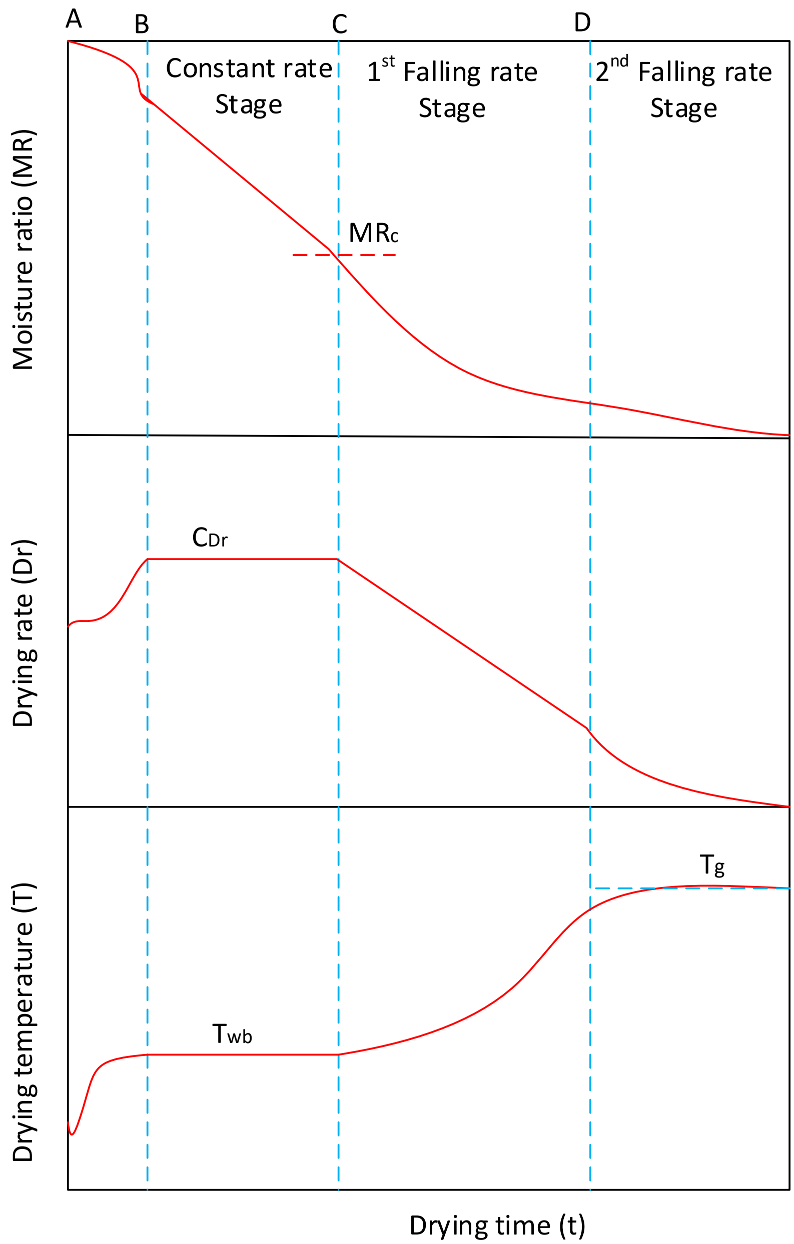


Figure 1: Drying curve of agricultural products that shows constant rate and falling rate periods.
(Onwude et al., 2016)

On the other way, gravity and capillary actions controlled the constant rate period and the surface of the product is highly affected. The product characteristics are significantly affected by drying conditions such as relative humidity, drying air velocity, and temperature in the constant rate period (Hashim et al., 2014).

Drying process parameters such as moisture content, water activity, drying air temperature, air velocity, humidity, microstructure, bulk density and porosity, chemical pretreatment, and vapor pressure have a great impact on the quality of agricultural commodities during the drying process. The quality of fruit and vegetables in trade is evaluated using different quality parameters such as flavor, nutritional composition, color intensity, and pungency as primary criteria. Solar dryers are designed by considering such kinds of parameters to identify the optimum operating conditions of the drying process.

2.1. Product characteristics

2.1.1. Moisture content

High moisture content is an important parameter for microorganisms' growth. Thus, reducing the water content of vegetables and fruits leads to minimize the activity of enzymes, bacteria, molds, and yeasts which deteriorate the quality of the products and therefore may bring long shelf life of the product (Prakash and Kumar, 2014). Moisture loss brings carotenoid loss while moisture gain increases browning. Thus, sorption characteristics of vegetables and fruits are very essential to design, modeling, and optimizing of storage and drying operation.

Sahar et al. (2015) reported the effect of moisture content (MC) on aflatoxin levels in the quality of red chilies based on 116 chili samples. About 37% had low MC (<10%), 29.4% had medium-low MC (10-12%), 18.9% had medium-high MC (12 < MC < 14%) and 14.7% was above 14%. The report indicated that the levels of average aflatoxin were 2.1 ± 1.1, 5.3 ± 4.2, 8.9 ± 5.9, and 37 ± 20 µg/Kg, respectively for the four chili categories. This indicated that aflatoxin was directly related to moisture content. The study concluded that low moisture content, that is, ≤ 10%, is very important to minimize aflatoxin level.

2.1.2. Water activity

Water activity or equilibrium relative humidity is the ratio of the equilibrium vapor pressure to the saturation vapor pressure. Water activity (α_w), is one of the critical criteria in fruit and vegetable handling mechanism to determine microorganism development and the release of toxin that indicates non-enzymatic and enzymatic browning formation in the products. The influence of water activity on fruit and vegetable quality during drying and storage was analyzed in detail in the work of (Getahun et al., 2020a).

$$\alpha_w = \left(\frac{P_w}{P_{ws}} \right)_T \tag{2.1}$$

Where P_w is equilibrium vapor pressure and P_{ws} is saturation vapor pressure. Fruit and vegetables have their water activity limit for which microorganisms stop growing. Beuchat (1981) reported that for the massive majority of mold and yeast $\alpha_w \approx 0.61$, bacteria grow at about $\alpha_w = 0.85$, fungi at $\alpha_w < 0.70$, etc.

2.1.3. Product physical property

The effect of bulk product properties such as volume, density, porosity, and shape factors during drying of fruits and vegetables was reported by Mayor et al. (2011). The structure of a food material may be characterized by its apparent density, solid density, bulk porosity, pore size distribution, specific volume, etc. Porosity is a measurement of pore or empty space of a material to that of the total volume which affects the transport, mechanical and textural properties of fruits and vegetables during drying (Omolola et al., 2017). The thickness of fruit and vegetables has a significant impact on the drying process. Apparent density is related to powdered and porous materials, it is determined by the mass of the product and its apparent volume. True density is the density excluding all pores and it is determined by the mass of the product and its true volume. The transport properties of foods such as diffusivity, permeability and thermal conductivity are significantly depend on the structure of the food and it is therefore very important to know the physical structure of the food material in order to determine its characteristics and quality during drying (Krokida and Maroulis, 2001).

2.2. Drying air properties

2.2.1. Temperature and relative humidity

It is known that drying at relatively high temperatures leads to the loss of volatile compounds, nutrients, and color. The dried chili quality such as nutrients and color attributes was studied by Wiriya et al. (2009) based on a tray dryer to determine the quality caused by drying temperatures (50-70 °C) which can be used to compare it with the sun drying process. The study indicated that a one-temperature system provided minimum values of chroma, lightness, and hue angle as compared to sun drying. On the contrary, the red color of chili was observed from the two-step temperature system. However, browning was also found at high temperatures due to a non-enzymatic browning reaction. Topuz (2008) studied the effect of water activity and temperature for the deterioration of paprika color and obtained a linear relationship between the rate constant and water activity of the color parameters. Vega-Gálvez et al. (2009) investigated temperatures impact on the texture, color, rehydration, vitamin C, antioxidant and total phenolic content of red chili. They concluded that rehydration was reduced along with temperature and maximum water holding capacity achieved at 50 °C. Vitamin C and total phenolic contents were reduced as drying air temperature decreased and maximum antioxidant activity was achieved at high temperatures. SIGGE et al. (1998) investigated the effect of temperature and relative humidity on the drying rates and drying times of green bell peppers (Capsicum annum L) at different dry-bulb air temperatures (55 °C, 60 °C, 65 °C, 70 °C, and 75 °C) and relative humidity (15, 20, 25, 30, 35 and 40%). The study indicated that drying rates normally increased as temperatures and RH decreased. The effect of temperature on drying rates became less noticeable with increasing RH.

2.2.2. Air velocity

Mass and heat transfer is highly enhanced by drying air velocity and resistance to mass transfer is directly related to drying air velocity. As drying air velocity increases, mass transfer resistance was also reduced. Hossain and Bala (2002) conducted experiments on thin-layer drying of red chilies through overflow and underflow of green chili with air temperature (40 to 65 °C), relative humidity (10 to 60%), and air velocity (0.10 to 1.0 m/s). The Page and single exponential empirical models were used to evaluate the drying properties of green chili and the parameters were also articulated as a function of relative humidity, air temperature, and air velocity. Bulent Koc et al. (2007) evaluated the impact of air velocity and chili particle size on ascorbic acid level, drying time, and color content using the response surface method in Turkey. The report showed that the minimum drying time, maximum ascorbic acid level, and the highest color value were determined at 1.3 m/s of drying air velocity.

3. Solar dryer systems

In solar drying, the heat essential to remove moisture from the product is mostly attained from solar energy. The air mass flow can be either forced or natural convection. The product is heated either through the passage of hot air within the product or the product directly absorbs solar energy or a combination of both (Ekechukwu and Norton, 1999). The general classification, performance, and empirical modeling of solar dryers have been reviewed by different scholars such as Mustayen et al. (2014), Kumar et al. (2016), Prakash et al. (2016), Fudholi et al. (2010), El-Sebaii and Shalaby (2012), Vijayavenkataraman et al. (2012), Sontakke and Salve (2012), Pirasteh et al. (2014) and Kiggundu et al. (2016), Mohana et al., (2020). Normally, solar dryers may be categorized as direct solar dryers, indirect solar dryers, and hybrid or mixed solar dryers.

3.1. Direct solar dryers

This kind of solar dryer is a natural convection type in which the product directly absorbs solar radiation. The idea of a direct solar dryer was originally initiated by Everitt and Stanley (Kumar et al., 2016) in 1976 as shown in Fig.2 to avoid the limitation of open sun drying. The main advantage of direct solar dryers is that the construction technique is simple and cheap. The product is easily protected from dust, rain, debris, dews, etc. Phadke and Walke (2015) reviewed the direct type solar dryer and indicated that these types of dryers are the simplest form of solar dryers which doesn't require any auxiliary equipment and is cheapest as compared to other types of solar dryers.

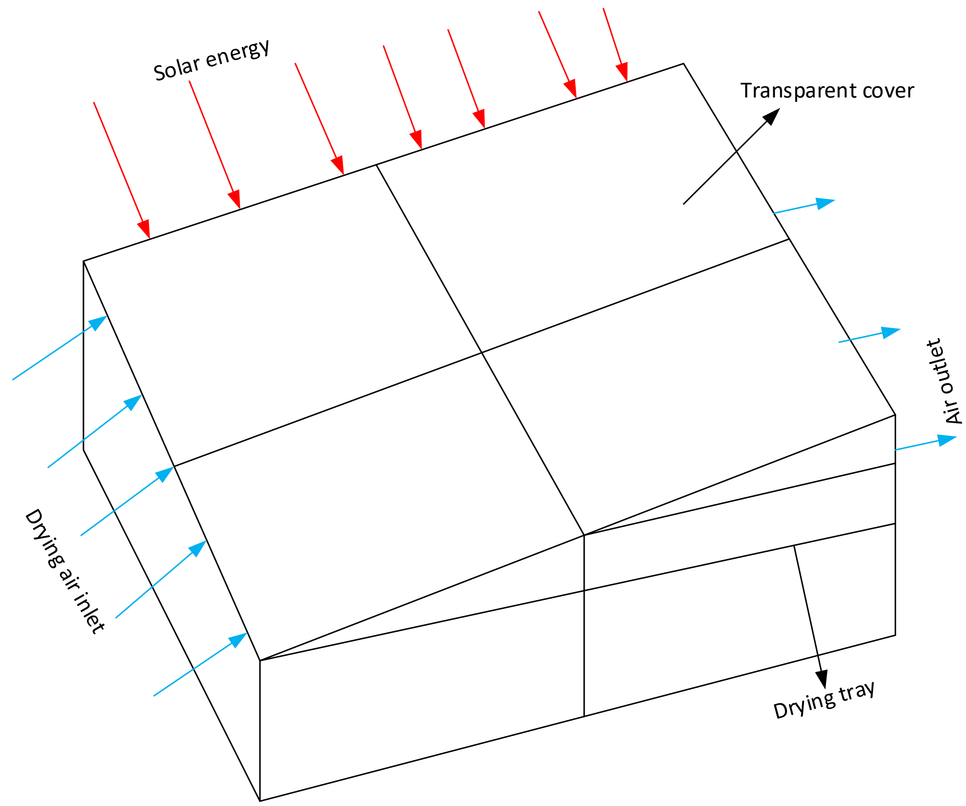


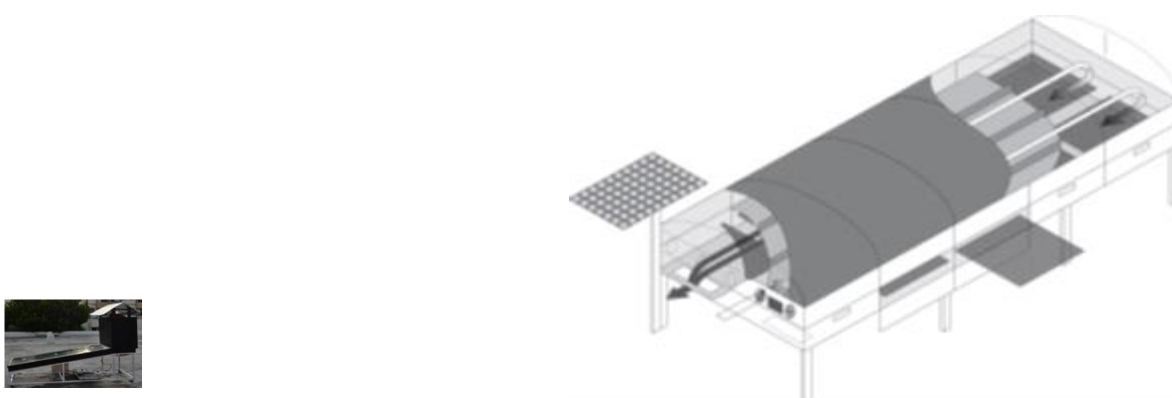
Figure 2: Direct solar dryer (Kumar et al., 2016).

However, overheating products, low product quality, and inadequate drying size are some of the drawbacks of direct solar dryers as compared to indirect solar dryers (Kumar et al., 2016).

3.2. Indirect Solar Dryer

In this type of dryer, first, the air is heated by the solar collector and the hot air mass flows through the product to be dried either in the form of natural or forced convection. Reports indicated that this kind of dryer improved the quality of the product and drying rate with a better control mechanism (El-Sebaii et al., 2002, El Khadraoui et al., 2017, Labed et al., 2016).

The development and performance of indirect solar dryers were reviewed by Shrivastava et al. (2014) and Phadke et al. (2015). Hegde et al. (2015) designed an active indirect type, low-cost, and environmentally friendly solar dryer to dry fruit and vegetables, specifically banana. The dryer has top (above absorber) and bottom (below absorber) airflow positions, forced flow with variable flow rates from 0-3 m/s, and two different mounting arrangements (conventional trays and wooden skewers) as shown in Fig. 3a. The solar collector thermal performance was determined by the ratio of energy output to the energy input. The result indicated that the efficiency of top and bottom flow configuration was found to be 27.5 %, and 38.21 % respectively. The study also showed that moisture content was found to be 3.1 % at 1 m/s air flow rate and the quality in terms of color, taste and shape was the best when compared to drying at 0.5 and 2 m/s air flow rate. On the other hand, reducing the rate of drying of fruit and vegetables is a key consideration in the solar drying processes. Stiling et al. (2012) determined the performance of an improved solar fruit dryer using concentrating panels which resulted in a temperature increment of 10 °C as compared to the usual solar dryer. The concentrating solar panels showed a considerable increase in drying rate of roma tomatoes on sunny days, with a 27% reduction of total drying time when compared to the normal dryer to reach the target moisture content. Mennouche et al. (2017) improved deglet-nour dates quality by indirect solar drying mechanism using hot water as a pretreatment agent which reduced the drying time and minimized the night storage problems. The dried product quality was evaluated by sugar composition, microbiological degradation, and color change and they concluded that the dryer has good product quality at 8 hr drying time and 1.2 m/s air velocity. Sharma et al. (2013) reported different optimization mechanisms such as the response surface methodology, genetic algorithms, artificial neural networks, and the Taguchi method for several solar drying operations to find out optimum drying parameters. The study that analyzed optimization of solar dryers in terms of cost, performance, and drying time includes (Sami et al., 2014, Gupta et al., 2013, Jadhav et al., 2010, Saini et al., 2017). Among the solar dryers, solar dryers with double pass have a high rate of drying which resulted significantly in a higher dryer performance and quality of the product. Banout et al. (2011) performed a comparative analysis between a double pass solar (DPSD) dryer, traditional open-sun drying, and solar cabinet dryer (CD) for red chili drying in central Vietnam as shown in Fig. 3b. The result showed that the drying times of DPSD and CD were 32 and 73 h and the overall drying efficiencies of DSPD and CD (on a wet basis) were 24.04% and 11.52%, respectively. The overall drying efficiency of open-sun drying (on a wet basis) was 8.03%. Furthermore, color values from the DSPD were higher than those from CD and open- sun drying based on ASTA method. Aflatoxin B1 formation was significantly reduced in DPSD dried chili (<0.250μg/kg) as compared to traditional open-air drying (11.980 μg/kg). Performance evaluation of red chili solar drying was also conducted by Fudholi et al. (2014) using exergy and energy analyses techniques. The result indicated that the efficiencies of the solar collector, drying system, pick-up, and exergy were 28%, 13%, 45%, and 57% respectively, at an average solar radiation of 420W/m^2 and a mass flow rate of air 0.07 kg/s. There are also other studies that have been conducted on solar drying of fruit and vegetable products to evaluate the performance of the dryer which include the work of Sreekumar et al. (2008), Hossain et al. (2008), Musembi et al. (2016) and Stiling et al. (2012).



a) b)

Figure 3: Indirect type solar dryer, a) cabinet type, b) Double-pass solar drier (DPSD) (Stiling et al., 2012, Banout et al., 2011) *respectively*.

The improvement of solar dryer design is a very important factor to maintain product quality and improve the performance of the dryer. Kabeel and Abdelgaied, (2018) analyzed a two-stage indirect type solar dryer performance supported with supplementary rewarming together with humidification-dehumidification (HDH) water purification systems as shown in Fig. 4. The report showed that the use of a two-stage dryer with reheating improved the moisture removal from the product by 71.78 % on average as compared to the first stage of the drying unit.

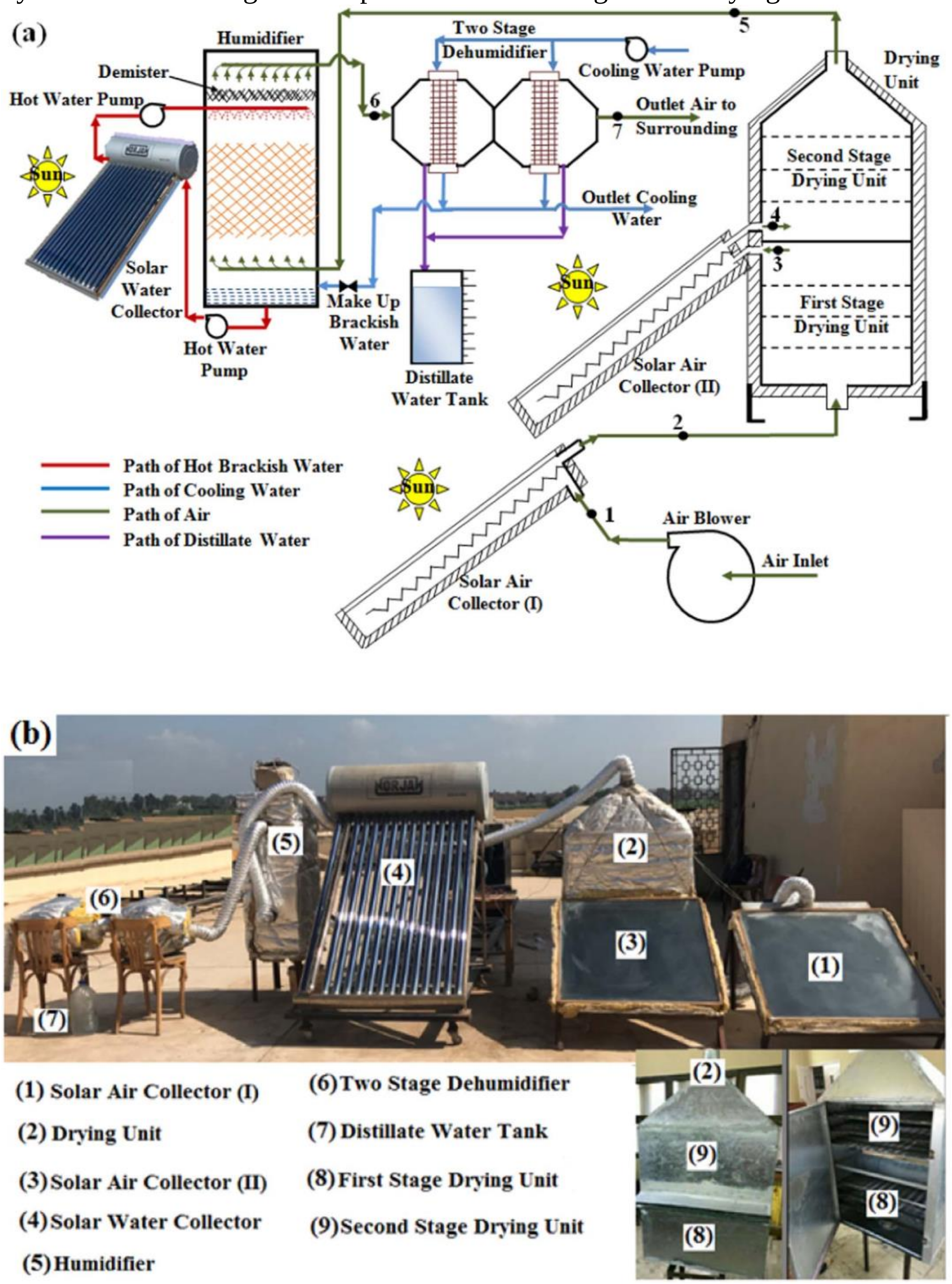


Figure 4: A two-stage indirect solar dryer with reheating coupled with humidification-dehumidification, (a) schematic diagram and (b) photo (Kabeel and Abdelgaied, 2018)

3.3. Mixed mode solar dryer

As the name indicates, drying happens simultaneously by absorbing solar energy directly through a transparent cover of the drying chamber and receiving hot dry air from a solar collector connected with the drying chamber. Hossain and Bala, (2007), developed a mixed type forced draft solar tunnel for red and green chilies in Bangladesh. The dryer is comprised of a drying tunnel, solar collector, and two fans driven by photovoltaics as shown in Fig.5. The drying took about 20h to reduce the moisture content of chili to the desired level.

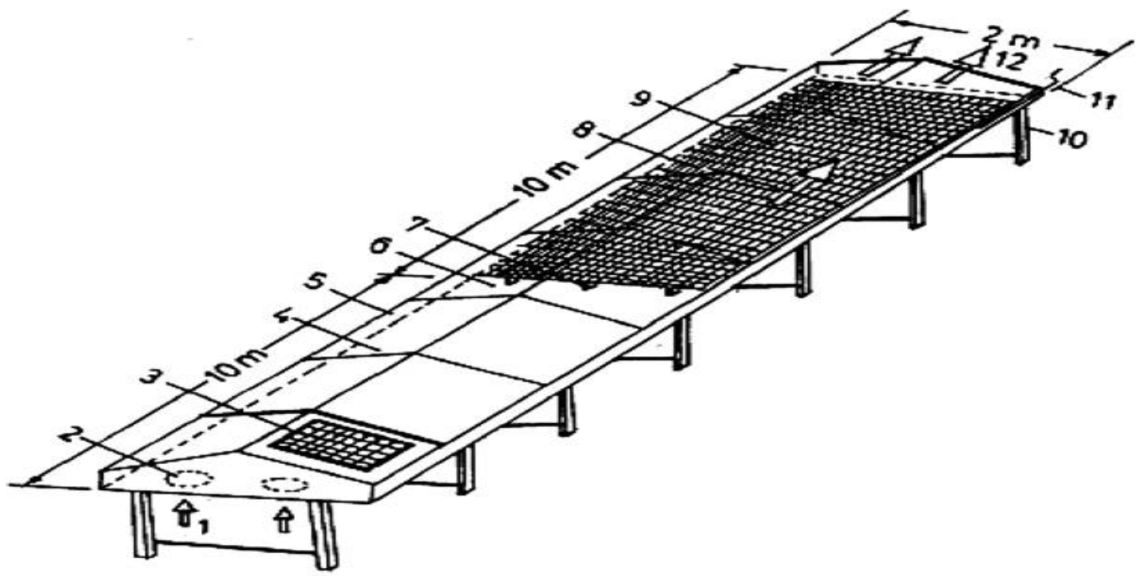
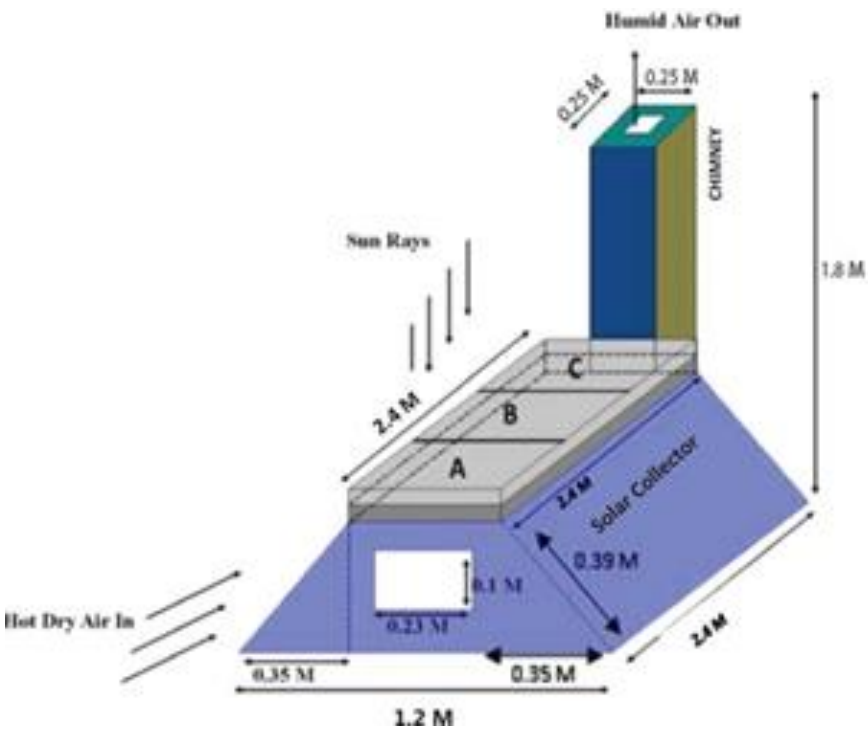


Figure 5: Solar tunnel drier: 1. air inlet; 2. fan; 3. solar module; 4. solar collector; 5. side metal frame; 6. outlet of the collector; 7. wooden support; 8. plastic net; 9. roof structure for supporting the plastic cover; 10. base structure for supporting the drier; 11. rolling bar; 12. outlet of the drying tunnel (Hossain and Bala, 2007).

Elkhadraoui et al. (2015) experimentally examined and economically evaluated a mixed type greenhouse solar dryer to dry grapes and red peppers. As shown from the schematic view in Fig. 6a, the dryer has a solar collector and chapel shaped greenhouse dryer. This dryer has a higher rate of drying than open-air drying and it can reduce the drying period of grapes and red pepper by 17 and 7h, respectively. Ayua et al. (2017) have been made a comparison between mixed-type solar dryers and direct solar dryers for African native chili and vegetable drying. As can be seen from Fig. 6b, the dryer was made of wood and comprised of a chimney, solar collector, and drying chamber. The mixed modes and the direct mode solar dryers dried vegetables at different rates with the mixed modes being faster for all products and can dehydrate vegetables to a moisture content of below 10% and therefore transform perishable vegetables into stable products with optimal quality.

a)



b)

Figure 6: The mixed modes solar dryer used for drying vegetables a) greenhouse dryer b) Cabinet dryer (ELkhadraoui et al., 2015, Ayua et al., 2017) *respectively*.

3.4. Greenhouse solar dryer

Most of the small scale industries need solar dryers with a relatively large loading capacity, where greenhouse and tunnel solar dryers are the most appropriate drying techniques in these scenarios. Greenhouse dryers are classified as solar tent, solar tunnel, improved solar tunnel, and roof type solar greenhouse dryers. However, a greenhouse solar dryer has its constraint in the drying process. The major limitation of the greenhouse dryer is energy loss on the north side of the dryer and non-uniform thermal energy distribution through the dryer (Gupta et al., 2012, Perea-Moreno et al., 2016). So far, different improvement mechanisms have been proposed by many researchers to reduce the limitations of the greenhouse dryer. One of these solutions is using energy storage materials that compensate for the energy losses of the greenhouse. The recent developments of greenhouse solar dryers have been exhaustively reviewed by Singh et al. (2018) and Prakash and Kumar (2014).

3.5. Solar electro hydrodynamic drying system

Electrohydrodynamic (EHD) is a new drying technique for agricultural products based on solar photovoltaic energy. The EHD has several benefits such as low equipment cost, energy-saving, low drying temperatures, and higher product quality (Defraeye and Martynenko, 2018, Dalvand et al., 2014). Dalvand et al. (2014) designed and constructed an EHD method, and the results showed that the rate of drying is highly influenced by the voltage applied voltage amount. As the applied voltage increases, the product moisture content decreases and energy efficiency, and consumption increases.

4. Drying kinetics and CFD modeling

In this part drying kinetics and CFD modeling were exhaustively reviewed and analyzed. Different thin layer drying modes were reviewed and discussed with respect to their advantage and disadvantage in most fruit and vegetable drying processes. Moreover, the CFD modeling based on thermal and hydrodynamic models were discussed. Macroscale CFD modeling papers were selected in the CFD modeling review which considers the performance of solar dryers.

4.1. Drying kinetics

Thin-layer drying models:

Thin-layer drying is defined as drying of a sample particle of one layer or slices. Due to its thin structure, the distribution of temperature can be easily assumed as uniform throughout the product which is very suitable for lumped heat transfer models. Mostly thin layer drying equations have been found to have extensive application due to their easiness of use and requiring less data unlike in complex distributed models (Erbay and Icier, 2010). Empirical, semi-theoretical, and theoretical models can be commonly used in thin layer drying as shown in table 2. Generally, the Semi-theoretical models can be formulated from (Rabha et al. 2017):

- Newton’s law of cooling: Comprises Page model & modified forms and Lewis model

- Fick's second law of diffusion: Comprises Single term exponential model and modified forms, two-term exponential model and modified forms, and three-term exponential model.

Normally, moisture diffusion of agricultural products in solar drying operation concerning position is expressed by Fick's first law and to time variation, it is expressed by Fick's second law and the second law of diffusion is determined as:

$$\frac{\partial M}{dt} = \left(D_{eff} \nabla^2 M \right), \tag{4.1}$$

where, D_{eff} is the effective diffusivity of moisture (m^2/s), M is the moisture content (d.b) at any time t (s). The moisture content (M) on a dry basis is given by:

$$M = \frac{w(t) - M_d}{M_d} \quad , \tag{4.2}$$

where *w(t)* is mass of wet materials (kg) at time instant t and M_d is mass of dry materials (kg).

It is obvious that the Lewis model is similar to Newton's law of cooling which is expressed as:

$\frac{dM}{dt} = -k\left(M - M_e\right)$, from this, the ratio of moisture can be determined as (Fudholi et al., 2013):

$$MR = \frac{M \ \ - M_e}{M_i - M_e} = \exp\left(-k * t\right) \ . \tag{4.3}$$

Table 2: Different mathematical models for the drying of fruits and vegetables

Model name	Model equation	Reference
Newton	$MR = \exp\left(-kt\right)$	(Liu and Bakker-Arkema, 1997, O'Callaghan et al., 1971)
Page	$MR = \exp\left(-kt^n\right)$	(Zhang and Litchfield, 1991)
Modified page	$MR = \exp\left(-\left(kt\right)^n\right)$	(Overhults et al., 1973, White et al., 1981)
Henderson and Pabis	$MR = \alpha \exp\left(-kt\right)$	(Koua et al., 2009)
Modified Henderson and Pabis	$MR = \alpha \exp\left(-kt\right) + b\exp\left(-gt\right) + c\exp\left(-ht\right)$	(Zenoozian et al., 2008)
Logarithmic	$MR = \alpha \exp\left(-kt\right) + c$	(Rayaguru and Routray, 2012)
Two-term	$MR = \alpha \exp\left(-k_o t\right) + b\exp\left(-k_1 t\right)$	(Sacilik, 2007)
Two-term exponential	$MR = \alpha \exp\left(-kt\right) + \left(1-\alpha\right)\exp\left(-k\alpha t\right)$	(Tunde-Akintunde, 2011)
Wang and Singh	$MR = 1 + \alpha * t + b * t^2$	(Omolola et al., 2014)

Diffusion approach	$MR = \alpha \exp(-kt) + (1-\alpha)\exp(-kbt)$	(Yaldýz and Ertekýn, 2001)
Midilli and Kucuk	$MR = \alpha \exp\left(-kt^{n}\right) + b * t$	(Tunde-Akintunde, 2011)

1

Where M_e is equilibrium moisture content, and M_i is initial moisture content, all are expressed on a dry basis, and k is the phenomenological constant (1/s).
On the other hand, Henderson and Pabis (Single term) model is derived from Fick's second law of diffusion and expressed as:

$$MR = \frac{M - M_e}{M_i - M_e} = \alpha \exp\left(-k * t\right) \tag{4.4}$$

where, α is a model constant.

In general, the Page model, along with the Midilli and other models are most suitable in describing the drying behavior of various fruits and vegetables as compared to the other thin layer drying models. Detail information about the derivation of each empirical model, the pros and cons of each model are found in Erbay and Icier (2010) and Ertekin and Firat (2017) reviews.

4.2. CFD modeling and simulation

Nowadays, modeling and simulation techniques are extremely important to develop efficient solar dryers and analyze and predict the performance of different kinds of solar drying systems. Generally, solar drying operation can be modeled using two different drying models:

- Based on principles of physics and mathematics
- Based on an empirical and semi-empirical approach

Modeling of solar dryers considering the principles of physics and mathematics depends on the characteristics of the product and the thermo-physical properties of drying agents and complex interactions between the two, which is very tough to quantify. Due to this challenge, most solar dryer investigators rely on empirical and semi-empirical drying models since these models give a direct correlation between the average moisture content and the drying time (Ertekin and Firat, 2017). Through intensive experimental trials, numerous empirical and semi-empirical models have been developed by different investigators, such as Lewis, Page, Newton models, and others (Table 2). Nevertheless, the empirical and semi-empirical drying models cannot explicitly define the physical properties of the drying process such as the mass transfer phenomena in the product and the surrounding environment. On the other hand, the physics and mathematics centered models mostly describe the mass and heat transport phenomena and thus used to determine the associated solar drying parameters (Yi et al., 2016).

Drying is characterized as a combined multiscale, multiphysics, and multiphase problem which is a very complex process. To describe explicitly this complex drying process, advanced mathematical modeling techniques like CFD, multiscale, multiphysics, and modeling of product properties and the associated spread of product property variability must be considered (Defraeye, 2014). The drying rate of any food product is highly dependent on drying air properties, product characteristics, dryer design, and operation procedures. However, it is very difficult, time consuming and expensive to pinpoint the optimum drying parameters by using experimental measurements. Thus, CFD is a simulation technique, in which it implements influential computer and applied physics and mathematics to model the systems for the prediction of mass, heat, and momentum transfer and to screen out the optimal design and operating conditions in the food drying process (Xia and Sun, 2002). The use of the CFD modeling technique is a very good option even though there are some complications in the modeling of turbulence (Oakley, 1994). The difficult natures of heat and mass transfer, multiphase fluid flow, and different radiation modeling of the solar drying process, triggered the use of CFD models in optimizing of design and operation of solar dryers.

Governing equations:

The flow of any fluid is described using the Navier's Stokes transport equations (Bird et al., 1960, Sanghi et al., 2017, Cârlescu et al., 2017, Romero et al., 2014a). These equations are formulated by considering momentum, energy, and mass balances in an infinitesimal element of fluid which results in a set of partial differential equations. The three dimensional Reynolds Average Navier Stokes (RANS) equations of mass, momentum, and energy are derived as follow:

Continuity equation:

$$\frac{\partial \rho}{\partial t} = \nabla\left(\rho \vec{u}\right) = 0 \qquad (4.5)$$

where $\vec{u}$ and ρ are velocity and density of air.

Momentum equation:

$$\frac{\partial\left(\rho \vec{u}\right)}{\partial t} = \nabla.\left(\rho \vec{u}\vec{u}\right) = -\nabla P + \bar{\bar{\tau}} + \rho \vec{g} + S_m \qquad (4.6)$$

where $\bar{\bar{\tau}}$ and S_m are Reynolds shear stress and momentum source term respectively.

Energy equation:

$$\frac{\partial\left(\rho E\right)}{\partial t} = \nabla.\left(\vec{u}\left(\rho E + P\right)\right) = \nabla.\left(-\vec{q} + \bar{\bar{\tau}}\vec{u}\right) + S_h \qquad (4.7)$$

Where, S_h, $\vec{q}$ and E are heat source term, heat flux vector, and total energy, respectively. The total energy is the summation of internal energy and kinetic energy which is given by:

$E = h - \frac{P}{\rho} + \frac{u^2}{2}$, where, h is the sensible enthalpy of air.

Mass transfer:

In solar dryers, water vapor is a scalar property and does not disturb the solutions of mass, momentum, and energy for dry air (Thorpe, 2008). The mass transport of the scalar property is, thus, solved independently with a general conservation equation:

$$\frac{\partial(\rho w)}{\partial t} = \nabla.(\rho \bar{u} w) = \nabla.(\rho D) + S_w \,, \tag{4.8}$$

where w is the humidity ratio (kg water vapor/kg dry air) and D is the water vapor diffusion coefficient which depends on temperature as defined by Sanghi et al. (2017). The moisture and heat source terms, S_w and S_h are determined as follow:

$$S_w = \rho_p \frac{\partial M}{\partial t} \,,\; S_h = \rho_p \frac{\partial M}{\partial t} L_v \tag{4.9}$$

where, L_v is water latent heat.

Turbulence models:

In CFD modeling, the effect of turbulence flow is predicted using different turbulence models and there are four types of turbulence models that have been commonly used for simulating solar drying processes (Kuriakose and Anandharamakrishnan, 2010, Malekjani and Jafari, 2018). These are:

- Standard k–ε model
- RNG k–ε model
- Realizable k–ε, satisfy normal stresses
- Reynolds Stress Model (RSM)

Among the turbulence models, the standard k–ε turbulence model is widely validated and commonly used in a region where there is no swirling flow. The turbulence dissipation rate ε and kinetic energy k are formulated as follows:

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho \vec{u} k) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon \tag{4.10}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \nabla.(\rho \vec{u} \varepsilon) = \nabla.\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + \frac{\varepsilon}{k}\left(C_{\varepsilon 1} P_k - C_{\varepsilon 2}\rho\varepsilon\right) \tag{4.11}$$

Where, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, constants and σ_k , σ_ε are the turbulent Prandtl numbers for k and ε. The turbulent (or eddy) viscosity μ_t is calculated from k and ε as $\mu_t = \rho C_\mu \frac{K^2}{\varepsilon}$

Porous media modeling:

Most vegetables and fruits are considered as porous media in the solar dryer process. The average velocity of the gas phase is obtained from Darcy's law. For the formulation of the momentum equation of the air flowing through the porous media, both inertial and viscous effects are also considered, and the so-called Darcy-Brinkman-Forchheimer equations are used (Nield and Bejan, 2006). The moisture transfer from the solid phase to the gas phase in the porous media is modeled through water vapor species transport equations as described by Jang and Arastoopour (2014) and Delele et al. (2009).

Radiation modeling:

In CFD modeling, different types of radiation models are considered for solar vegetables and fruit dryers (Yunus and Al-Kayiem, 2013, Khaldi et al., 2017, He et al., 2018, Blanco-Cano et al., 2016). For instance, in the radiation model of P-1, the radiation flux, q_r is derived as (Yunus and Al-Kayiem, 2013):

$$q_r = \frac{1}{3\left(\alpha + \alpha_s\right) - C\sigma_s} \nabla G \quad , \tag{4.12}$$

where σ_s is the scattering coefficient, G is radiation incident, α is the coefficient of absorption and C is the coefficient of linear-anisotropic phase function.

CFD model solution procedures

The hydrodynamic solar dryer models are discretized and computed using different numerical techniques. Among the different discretization techniques, the most important ones are the finite element, finite volume and finite difference methods which are commonly used in many commercial CFD software programs such as ANSYS, COMSOL, OpenFOAM, STAR CCM, PHONICS, and FLOW 3D (Stone1 et al., 2016).

The numerous advanced modeling and simulation techniques for food dryer systems are reviewed so far by different researchers (Prakash et al., 2016, Jamaleddine and Ray, 2010, Defraeye, 2014, Perré, 2011). Those advanced modeling and simulation techniques were based on the microscale level and mainly focused on the food item drying excluding the overall solar dryer modeling and simulation. In this scenario, there were various studies which were conducted to investigate the optimum drying parameters, such as the works of Kaya et al. (2008), Lamnatou et al. (2010), Khan and Straatman (2016), Defraeye and Radu (2017), Curcio et al. (2016), Prukwarun et al. (2013), Misha et al. (2013) and Tzempelikos et al. (2012).

However, the quality of dried food depends also on the type of dryer, temperature, humidity, pressure, and velocity distribution at each position in the solar dryer chamber. Uncontrolled solar drying deteriorates the nutritional value of foods, thus CFD modeling and simulation of solar dryers is a good option to optimize the drying parameters and product quality. So far, there were inadequate research outputs that applied the CFD modeling and simulation of solar dryers in fruit and vegetable drying systems. Among those studies, Romero et al. (2014b) conducted a simulation of the vanilla solar drying process using CFD to investigate temperature distribution. In the solar collectors, the simulation results indicated that temperature distribution was found in good agreement with the experimental values rather than in the cabinet dryer due to the assumption of a fixed heat transfer coefficient. They suggested that it is necessary to express a flexible heat transfer coefficient as a function of time to attain uniform temperature distribution inside the cabinet dryers. Comparable investigation was conducted by Amanlou and Zomorodian (2010) using CFD for designing a new cabinet fruit dryer with a side-mounted plenum chamber using seven geometrical configurations (Fig. 7) to analyze velocity and temperature of drying air homogeneity through the dryer chamber. The standard k-ε model was considered in this CFD simulation. The report showed that design (b) was the most suitable design for obtaining uniform air temperature and velocity distributions in the drying chamber among the other alternative geometries. The experimental and simulation results showed good correlation coefficients of 99.9% and 86.5% for drying air temperature and air velocity in the drying chamber, respectively.

Yunus and Al-Kayiem (2013) modeled and simulated the velocity and temperature distribution of the cabinet solar dryer using the RNG k-epsilon model. The P-1 radiation model and finite volume discretization technique were used in the simulations. The simulation result showed a high-temperature spot with very low velocity underneath the solar absorber and this is an indication of the poor design of the solar dryer as they suggested (Fig. 8). Moreover, this research result showed that non-uniform drying air and temperature distribution through the solar cabinet dryer tray.

Sanghi et al. (2018) performed CFD simulation of drying of corn through natural convection solar dryer at fair and overcast weather conditions to visualize temperature, humidity, and air velocity distributions of the dryer considering dual-band spectrums.

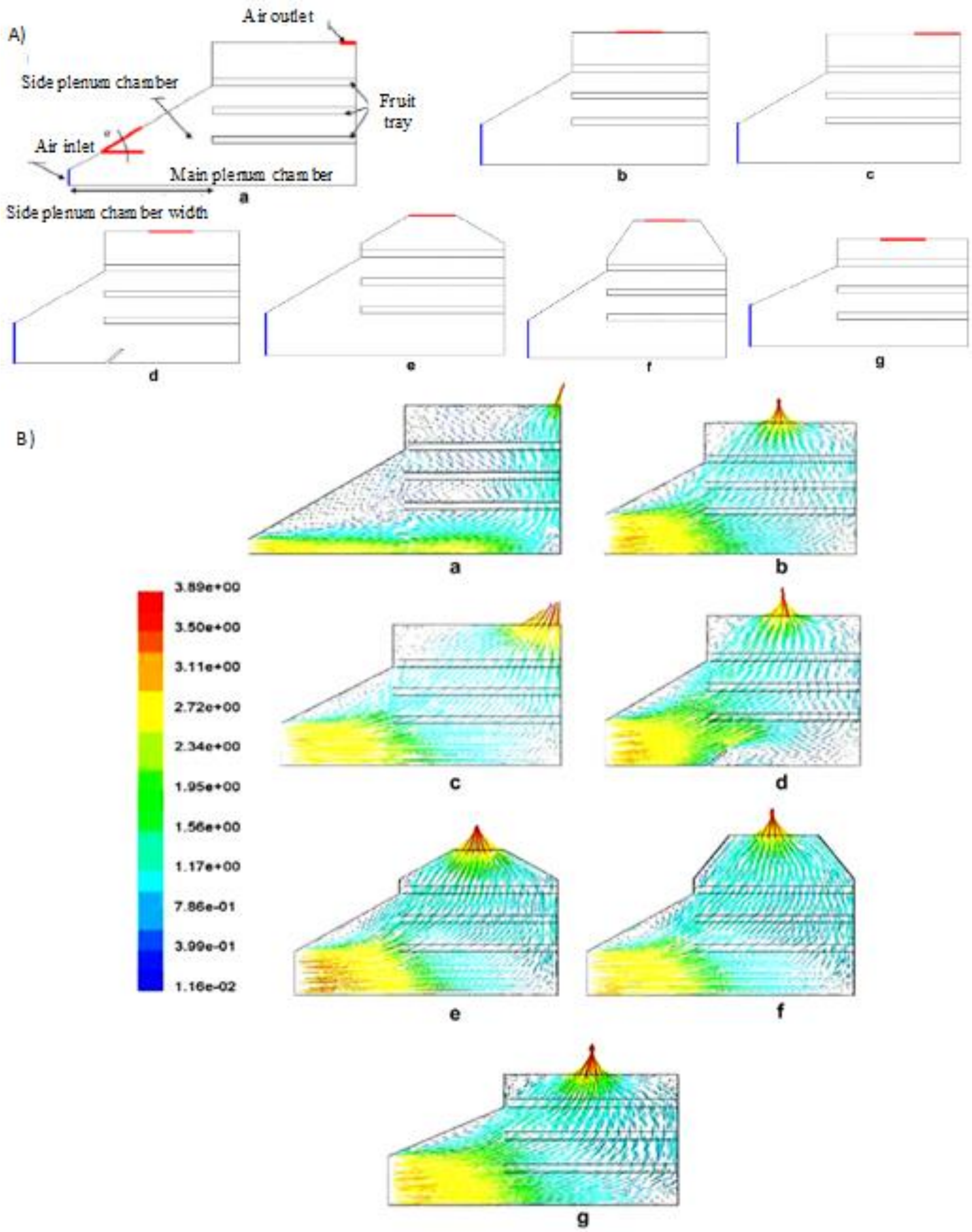


Figure: 7. Air velocity distribution profiles for the seven designs (A) and CFD simulation results (B) at inlet air velocity = 3 m s^{-1} (Amanlou and Zomorodian, 2010).

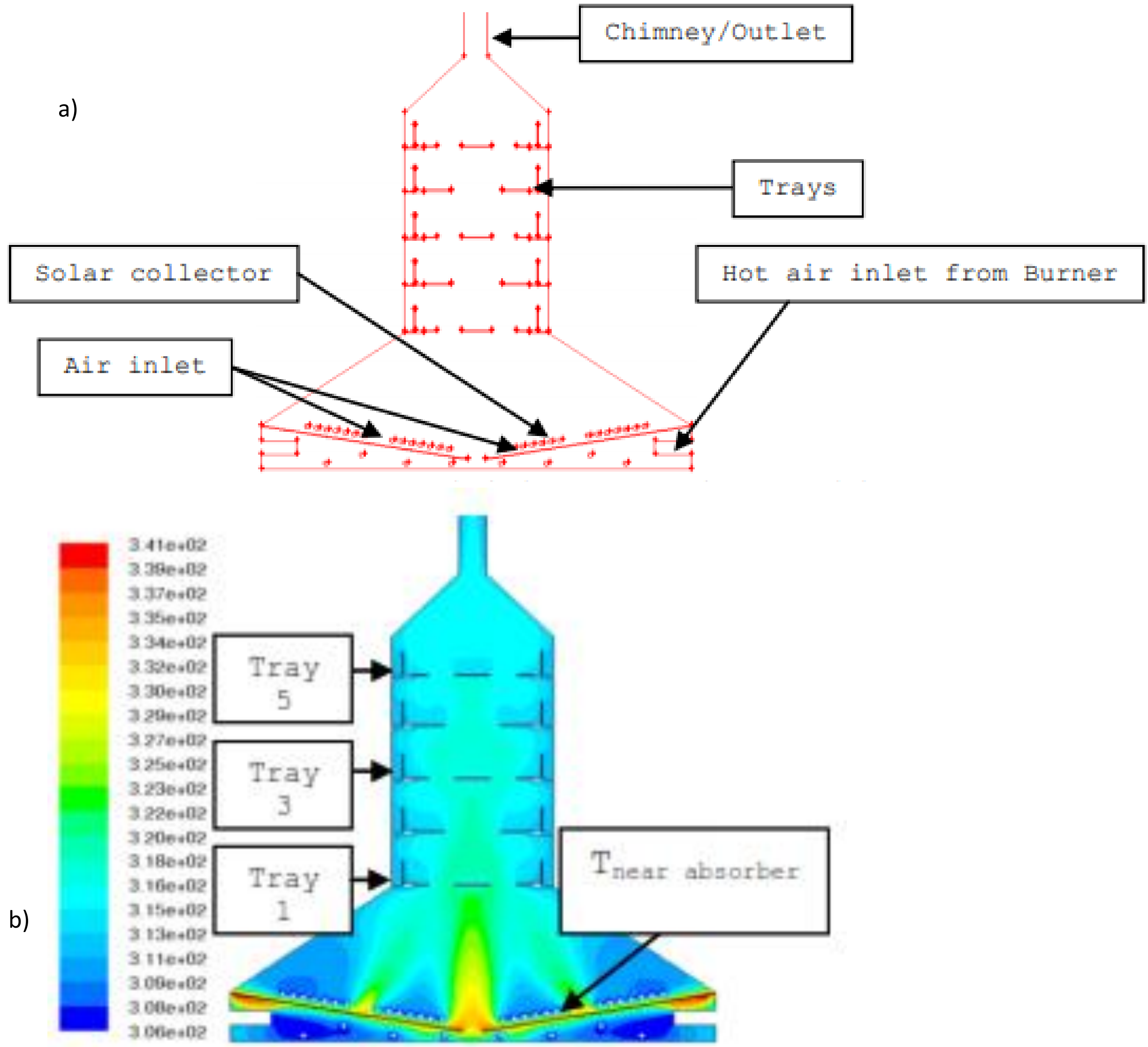
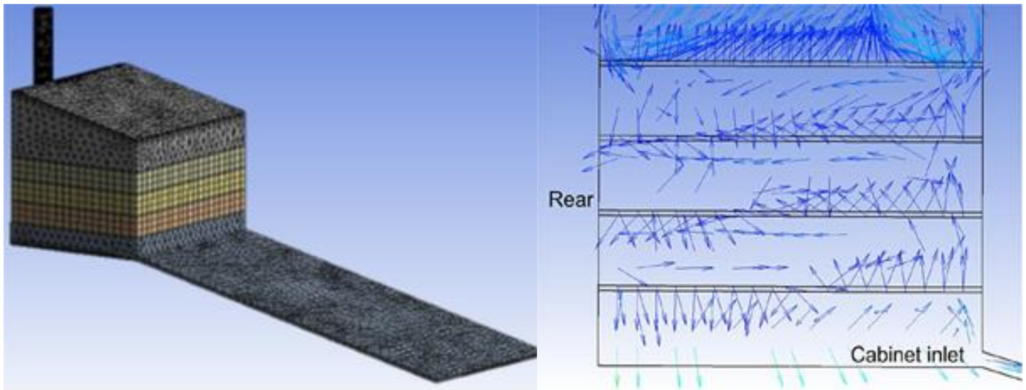


Figure 8: Solar cabinet dryer model (a) and temperature contours (b) in degree centigrade, (Yunus and Al-Kayiem, 2013).

The model was validated with experimental results, which showed an overestimate of humidity (21.4%) and temperature (8.5%). The experimental humidity profile showed that there was stagnation in the airflow (Fig. 9) of the dryer which showed an accurate prediction of the model and the overcast weather predicted moisture removal was 32% less than the simulated fair-weather case. Other studies analyzed the distribution of temperature and air velocity inside cabinet solar dryers using CFD (Ghaffari and Mehdipour, 2015, Darabi et al., 2015, Alqadhi et al., 2017, Abhay et al., 2018, Tegenaw et al., 2019a, Sanghi et al., 2018, P. Mutabilwa and Nwaigwe, 2020).



a b

Figure 9: Geometry of a cabinet dryer (a) and air flow profile at the center plane (b) of a cabinet dryer (Sanghi et al., 2018).

Valarmathi (2018) performed computational fluid dynamics analysis on greenhouse solar dryers for free and forced convection processes to analyze the average temperature distribution of the dryer. The result indicated that the maximum temperature obtained by forced convection was 71°C for 0.025 kg/s mass flow rate, which was 41% more than that obtained by natural convection as shown in Fig.10. However, this study did not model the moisture transport phenomena. Other CFD modeling and simulation of greenhouse solar dryer of agricultural commodities include. (Lokeswaran and Eswaramoorthy, 2013, Kumar et al., 2017, Khanlari et al., 2020).

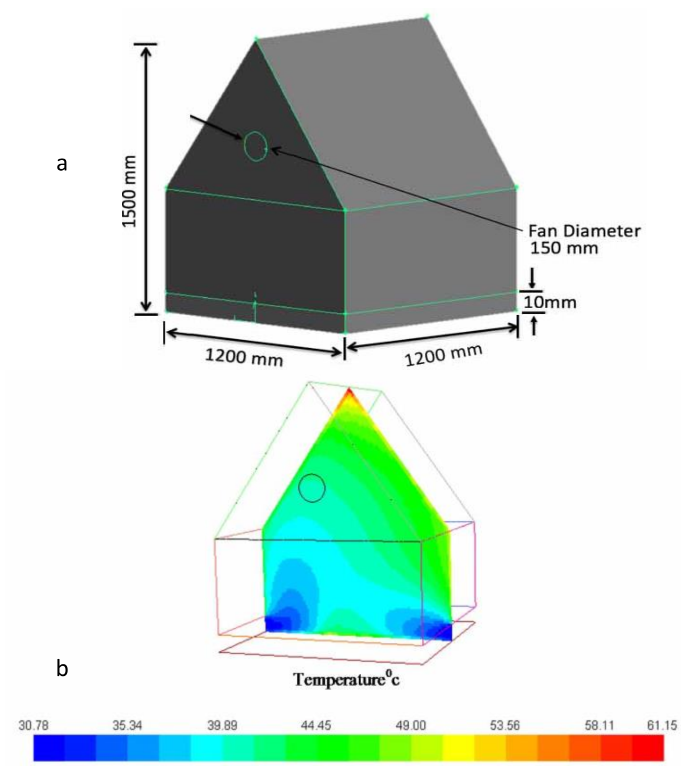


Figure 10:3-D model of the dryer (a) and temperature contour (b) of the midplane (Valarmathi, 2018).

Iranmanesh et al. (2020) modeled and simulated, through CFD, a solar cabinet apple dryer that has an evacuated tube solar collector (ETSC) and a PCM thermal energy storage as shown in Fig.11. Three-level of drying air flow rates (0.025, 0.05, and 0.09 kg/s) were implemented with and without PCM to evaluate the dryer efficiency. The results showed that using PCM increases the input thermal energy by 1.72% and 5.12% for the air flow rates of 0.025 and 0.05 kg/s respectively, but an excessive increase in air flow rate (up to 0.05 kg/s) decreases input thermal energy. The maximum overall drying efficiency was 39.9%.with PCM at the air flow rate of 0.025 kg/s.

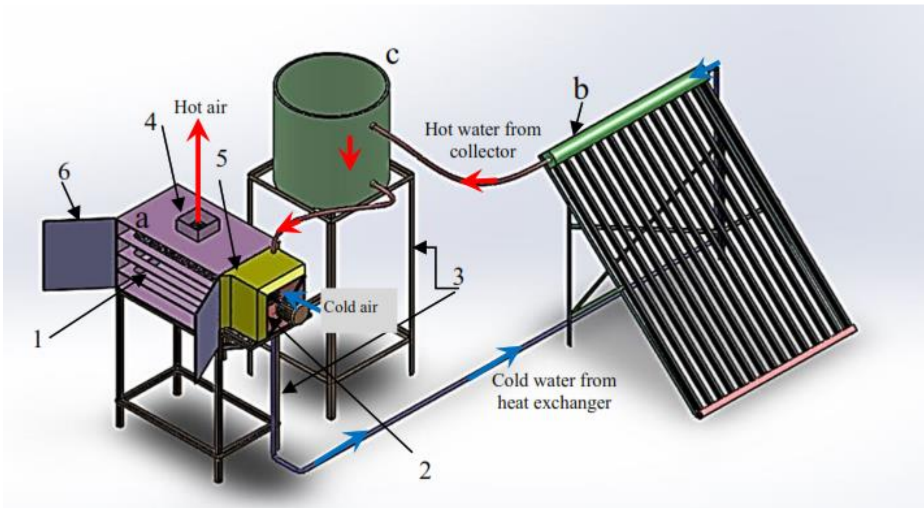


Figure 11. The schematic of solar cabinet dryer including a) Dryer: 1- sample trays and cabinet, 2- fan, 3- chassis, 4- exhaust channel, 5- Heat exchanger, 6- doors; b) ETSC; c) Storage tank and PCM container inside (Iranmanesh et al., 2020).

The result also indicated that the maximum drying temperature of the cabinet dryer was 70 ºC at the mid plan as shown in Fig. 12.

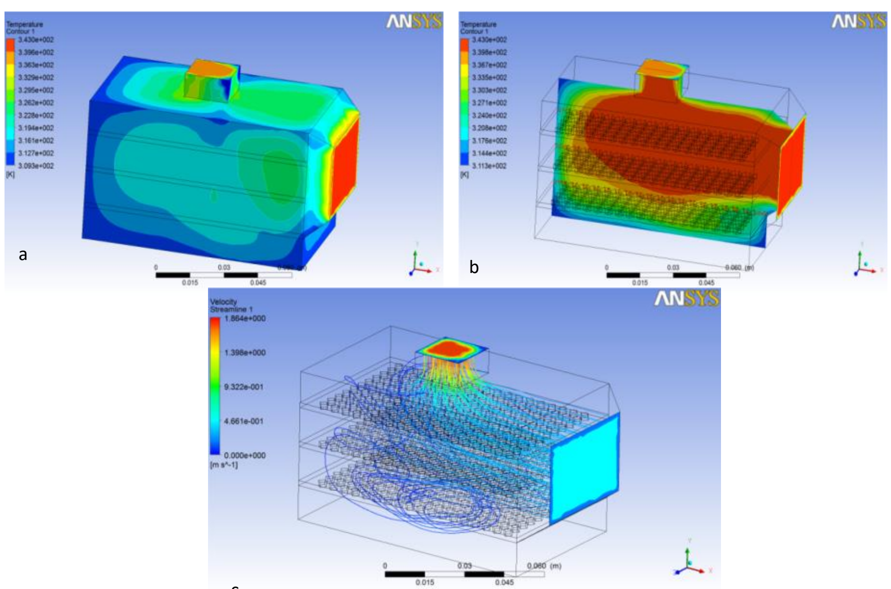


Figure 12. Temperature contours (a) the wall (b) midplane and (c) velocity streamlines of the cabinet dryer at 14:00 for airflow rate of 0.025 kg/s (Iranmanesh et al., 2020).

Getahun et al., (2020) investigated the potential of a solar cabinet chili dryer through rigorous computational fluid dynamics using a double-pass solar collector and the drying chamber had uniform drying air velocity distribution as shown in Fig.13. The maximum drying chamber temperature was in the range of 34 -39 ^{o}C.

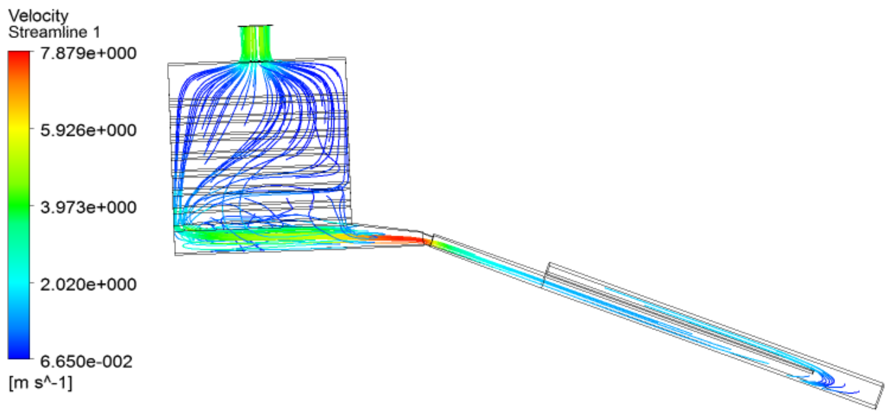


*Figure 13. Velocity streamline of the chili drying chamber (*Getahun et al., 2020)

Güler et al. (2020) have been studied, using CFD, an indirect double-pass solar dryer with and without mesh absorber modifications (DPISDMA) to enhance the efficiency of the drying system. The Pepino fruit (Solanum muricatum L.) samples in two thicknesses were used in the experimental study. The results showed that using mesh modification increased the thermal performance of the collector in DPISDMA for the thin sample thickness and the average efficiency was 75.3% and the dryer efficiency was 23.08%. The drying chamber maximum temperature was 42 ^{o}C as shown in Fig.14.

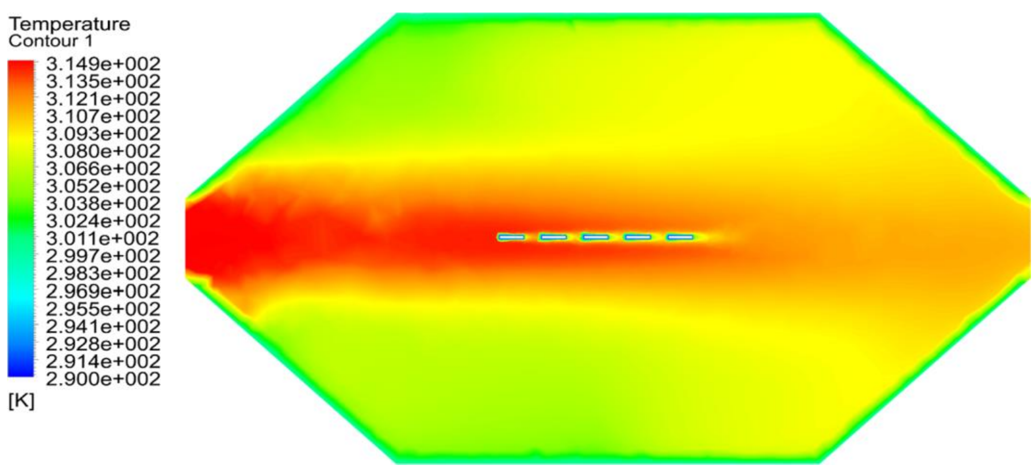


*Figure14. Temperature distribution in the drying chamber (*Güler et al. 2020).

Romuli et al. (2019) investigated the technical performance of an inflatable solar dryer (ISD) to dry amaranth leaves (Amaranthus spp.) and analyzed the uniformity of air distribution in the ISD. High drying air velocity was observed in the inlet of the ISD dryer as shown in Fig.15. The maximum and minimum temperature inside the ISD could reach up to 69.4 ^{o}C during the day and 13.4 ^{o}C during the night respectively.

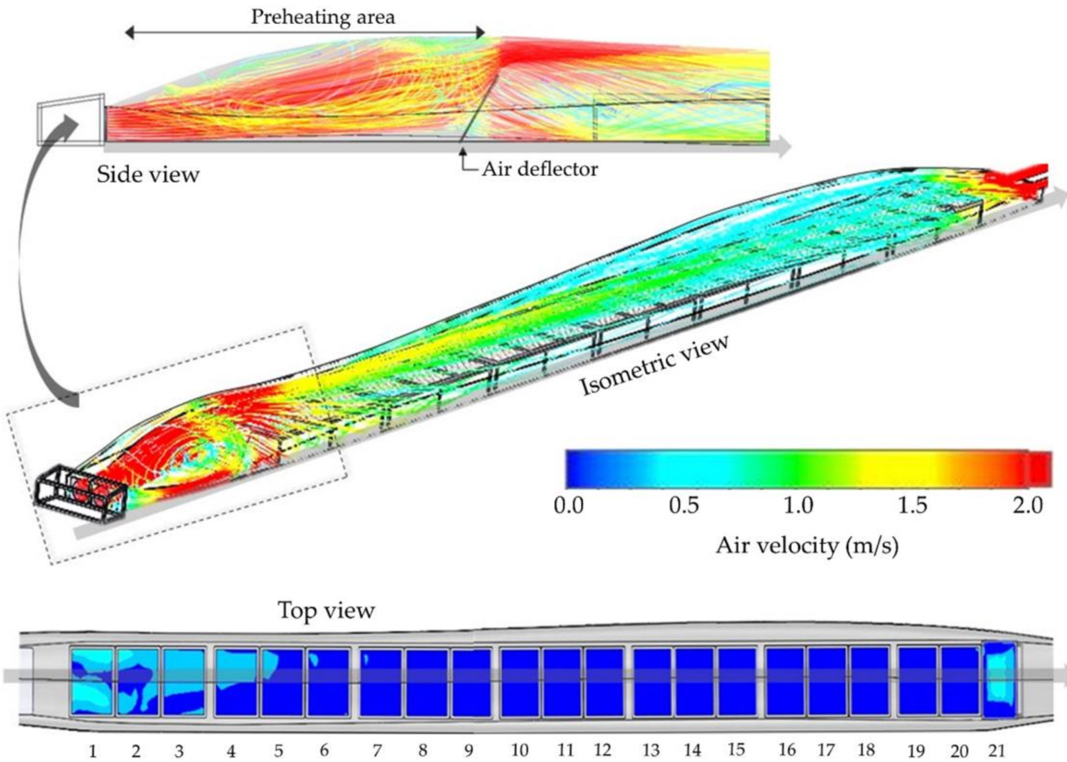


Figure 15. Visualization of airflow distribution and direction in the ISD (isometric and side view) and vertical flow through the 21 trays (top view) (Romuli et al., 2019).

Tegenaw et al., (2017, 2019b) analyzed the marching heat transfer in a solar food (sweet potato) dryer by using both lumped capacitance modeling and computational fluid dynamics (CFD) techniques. The CFD model is used to simulate the transient heat transfer and airflow within the dryer. The result indicated that the two models predicted both a steady-state temperature rise of 40 °C within the drying cabinet. The marching heat transfer phenomenon from CFD modeling (Fig.16) also showed that the spatial distributions of temperature were uniform after 30 min, which validating the assumption of lumped capacitance modeling.

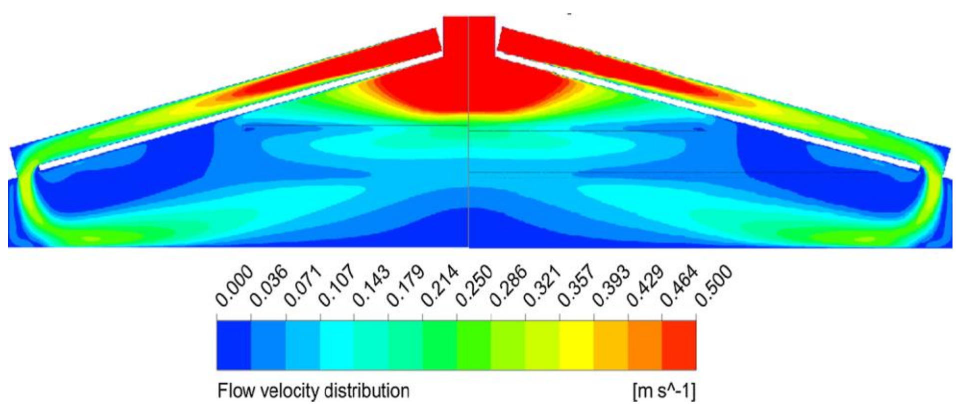


Figure 16. Contour plot of velocity distribution of the solar sweet potato drying cabinet (Tegenaw et al., 2019b)

Román-Roldán et al., (2019) performed computational fluid dynamics analysis of heat transfer in a greenhouse solar dryer "chapel-type" coupled to an air solar heating system to investigate the distribution of temperature, turbulent kinetic energy (TKE), and velocity of air inside the greenhouse solar dryer (GHSD) using ANSYS FLUENT. The result showed that the TKE was found in the range of 1.27 m^2/s^2 and 6 m^2/s^2 with an average of about 1.6 m^2/s^2 for the entire greenhouse dryer (GHD) volume. Nearly uniform temperature distribution was found in the whole volume of the GHD, at an average magnitude of 315 K, which was very suitable for a good quality drying process. The mean air velocity at 1 m height of dryer was 0.71 m/s.

Ghaffari and Mehdipour, (2015) investigated the performance of cabinet solar dryer using CFD and the model was then optimized by incorporating some baffles to attain high efficiencies and speed up the drying process. The result indicated that there was a kind of temperature homogeneity in the drying process in each tray as shown in Figure 17.

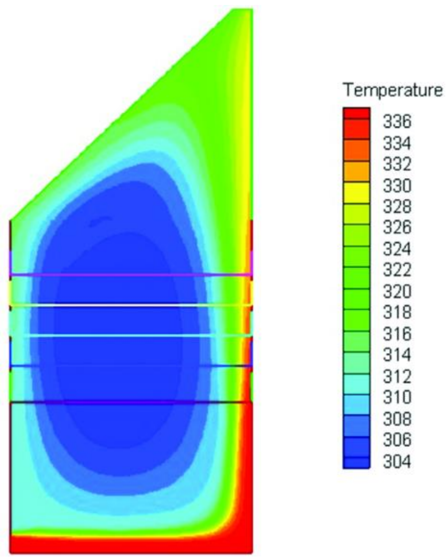


Figure 17: Temperature contour of the drying chamber in kelvin (Ghaffari and Mehdipour, 2015).

Khanlari et al., (2020) assessed the performance improvement of a greenhouse apricot dryer using a cost-effective solar air heater through CFD as shown in Fig.18 a. The result showed that drying temperature was uniformly distributed through the greenhouse dryer with tube-type solar air heater efficiency of 45.6-56.8% (Fig.18 b).

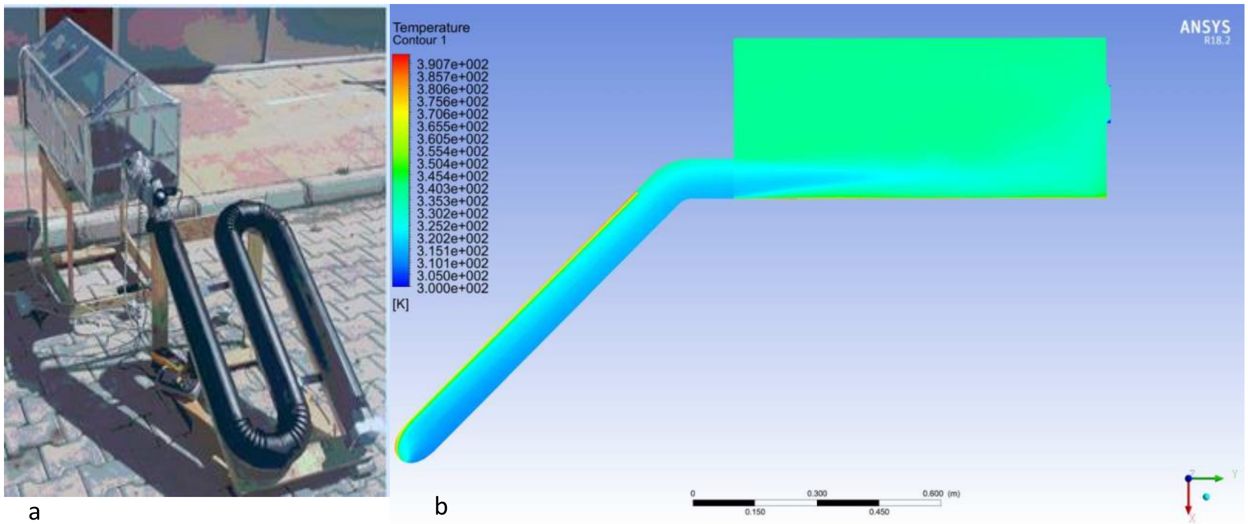


Figure 18: Apricot drying process in the solar greenhouse dryer, a) drying set up & b) drying temperature distribution inside the tube type collector (Khanlari et al., 2020).

Babu et al., (2020) performed CFD studies on different configurations of a drying chamber for thin-layer drying of leaves to obtain uniform drying air distribution throughout the drying chamber. The best configuration of the drying chamber and construction detail was investigated. Alimohammadi et al., (2020) reported a thermal study of a solar dryer that has PCM and parabolic trough solar collectors (PTSC) using experimental and CFD methods. The simulation process was performed to predict thermal variations in the receiver tube and storage tank by CFD using Nano-fluid (Al2O3, 4%), engine oil (10W40), glycerin, and water to dry apple slices. The results revealed that the total input thermal energy of the dryer was found as 18.46 MJ, 17.76 MJ, 17.36 MJ, and 16.80 MJ for oil, glycerin, nano-fluid, and water, respectively that were suitable for apple drying processes. P. X. Mutabilwa and Nwaigwe, (2020) evaluated the drying of banana through a double-pass solar collector (DPSC) and theoretically analyzed using a CFD model to obtain uniform drying air and temperature distribution. The result showed that the DPSC achieved an optimal peak outlet temperature of 72 °C with a maximum operational efficiency of 72.5% that was important for drying of banana.

Aukah et al., (2018) also predicted airflow and temperature distribution in hybrid solar-biomass dryer using computational fluid dynamics for maize drying and the result revealed spatial homogeneity of drying air condition.

Khaldi et al., (2018) applied CFD for studying the thermal and dynamic behavior of an indirect solar figs dryer. They analyzed the effects of air inlet size and thickness of the packed bed on the dynamic and thermal behaviors of the dryer with and without a packed bed. From this study, they concluded that increasing the inlet size from 0.04 m to 0.10 m can accelerate the extraction of air by about 13% and reduced the maximum crop temperature by about 14%. The packed bed can reduce the mass flow rate by 22% and the fluctuations of air temperature by 1.3%. A packed bed with a thickness of 0.15 m can extend the operating time of the dryer up to 23%. The temperature and velocity distributions of this dryer was presented in Fig.19.

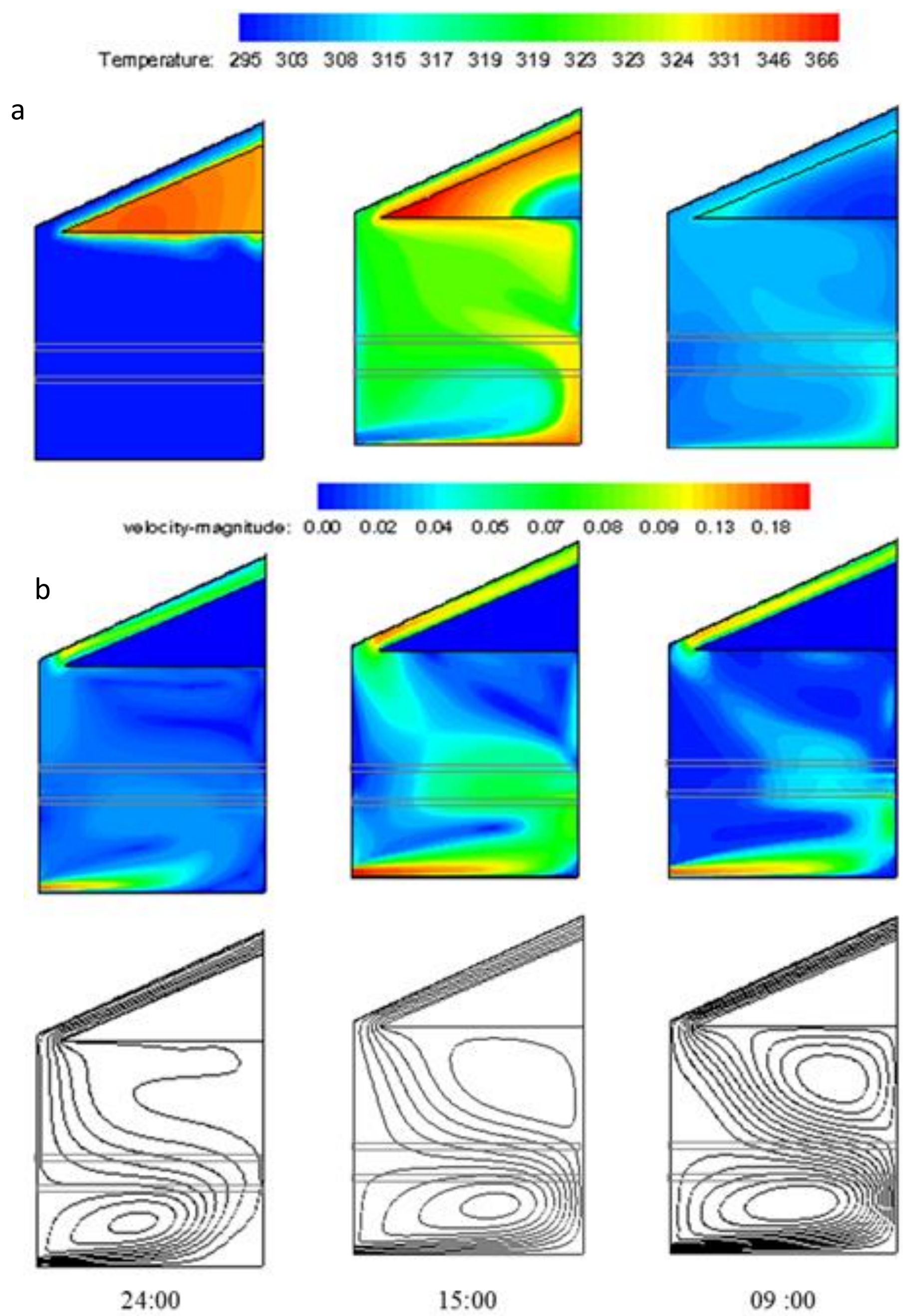


Figure 19: Temperature (a) and velocity distribution (b) of solar fig dryer using CFD (Khaldi et al., 2018).

Different vegetable and fruit solar dryers that applied CFD modeling and simulations are summarized in detail as shown in Table 3.

Table 3. Previous studies that apply CFD modeling in the analysis and evaluation of solar dryers for fruit and vegetable products

Type of solar dryer	Produce type	CFD Software	Study criteria	Porous media approach	Turbulence model	Radiation model	Mesh type	Findings	Reference
Cabinet	Vanilla	ANSYS - FLUENT	Distribution of temperature, moisture, and RH	No	Transient and laminar flow	-	-	62% reduction of moisture within 1 month	(Romero et al., 2014a)
Cabinet	-	ANSYS - FLUENT	Distribution of air velocity and temperature	No	RNG k–ε model	P-1 radiation model	Unstructured/tri mesh	Non-uniform temperature and velocity, max temperature = 46 ºC, max velocity = 0.26m/s	(Yunus and Al-Kayiem, 2013)
Cabinet	Corn	ANSYS - FLUENT	Distribution of temperature, air velocity, moisture, and RH	Yes	RNG k–ε model	Two-band model	Mesh independent	Simulation result similar to experimental with some over-prediction of temperature (8.5%), Rh (21.4%)	(Sanghi et al., 2018)
Cabinet	Grape	C++	Distribution of temperature, air velocity, and RH	Yes	k–ε model	-	Tetrahedral non-uniform	Drying time = 7days without baffle and 2.5 days with, T_{max} = 68 ºC, uniform velocity with V_{max} = 0.126m/s, product humidity reduced from 82% to 18%	(Ghaffari and Mehdipour, 2015)
Mixed-mode dryer	-	ANSYS - FLUENT	Distribution of temperature and air velocity	No	k–ε model	Discrete transfer type (DTRM)	Structured rectangular	Uniform velocity and temperature with V_{max} = 3.9m/s and T_{max} = 66.85 ºC.	(Alqadhi et al., 2017)
Greenhouse	-	Gambit software	Distribution of temperature	No	-	-	Hexahedral unstructured	Uniform temperature with T_{max} = 71ºC, mass flow rate = 0.025kg/s	(Purusothaman and Valarmathi, 2018)
Greenhouse	-	ANSYS - FLUENT	Temperature distribution	No	-	Discrete transfer type (DTRM)	Tetrahedral	Variable temperature with T_{ma}x = 68 ºC.	(Lokeswaran and Eswaramoorthy, 2013)
Greenhouse	Potato, tomato flakes	ANSYS - FLUENT	Temperature and Rh distribution	No	k–ε model	-	Hexahedral unstructured	Variable temperature wit T_{max} = 57 ºC.	(Kumar et al., 2017)

Cabinet with PCM	Apple slice	ANSYS-FLUENT	Distribution of temperature & air velocity	pseudo	k–ε model	-	Hexahedral & Tetrahedral	Drying efficiency = 39.9%, T_{max} = 69 ºC, mass flow rate = 0.025kg/s, with some uniformity, thermal energy increased by 1.72% with PCM, drying time with PCM = 810 to 870min, without PCM = 900 to 960min.	(Iranmanesh et al., 2020)
Cabinet with double pass air collector	Red chili	ANSYS CFX	Distribution of temperature & air velocity	yes	k–ε model	Monte Carlo	Hexahedral unstructured	Uniform velocity distribution with T_{max} = 39 ºC.	(Getahun et al., 2020b)
Cabinet with double pass air collector	Pepino	ANSYS-FLUENT	Distribution of temperature & air velocity		k–ε RNG	-	-	Good flow visualization with V_{max} = 2.7m/s and T_{ma}x = 42 ºC, drying time =15 hours, highest drying efficiency = 23.08%	(Güler et al., 2020)
inflatable solar dryer (ISD)	Amaranth leaves	-	Distribution of air velocity		-		-	Non-uniform drying with T_{max} = 69.4 ºC and V_{max} = 1.5m/s, drying time = 68 hours, final moisture content = 11.6%	(Romuli et al., 2019)
Cabinet	Sweet potato	ANSYS-FLUENT	Distribution of temperature & air velocity	Yes	k–ε model	-	Tetrahedral unstructured	Uniform temperature after 1h with T_{max} = 67 ºC,non- uniform flow velocity with V_{max} = 0.5m/s	(Tegenaw et al., 2019a)
Greenhouse	Any food	ANSYS-FLUENT	Distribution of temperature, air velocity & TKE	No	k–ε model	DO	Hexahedral structured	Uniform temperature distribution with T_{max} = 44 ºC, $V_{average}$ = 0.71m/s, TKE = $1.6m^2/s^2$	(Román-Roldán et al., 2019)
Greenhouse	apricot	ANSYS-FLUENT	Distribution of temperature & air velocity	-	k–ε model	-	-	Good visualization of flow, tube type air heater out let temperature = 50.8 ºC, drying time = 255 minutes (30% reduction) dryer average efficiency = 45.6 to 56.8%	(Khanlari et al., 2020)
Tray dryers	Leaves	ANSYS-FLUENT	Distribution of temperature & air velocity	Yes	k–ε model	-	hexahedral structured	Low-pressure drop, high mass transfer rate and uniform flow at the optimal design point	(Babu et al., 2020)

Cabinet	Banana	ANSYS	Distribution of temperature & air velocity	No	SST-k-w	DO	Hexahedrons	Good flow visualization with maximum collector outlet temperature of 72 ºC, collector efficiency = 72%	(P. X. Mutabilwa and Nwaigwe, 2020)
Cabinet	Figs	ANSYS - FLUENT	Distribution of temperature & air velocity	Yes	k–ε model	-	-	Good flow visualization, moisture reduced from 1.9 to 0.76kg water/kg dry solid within 22 hours of drying time	(Khaldi et al., 2018)

5. Quality attributes of solar-dried fruits and vegetables

Solar drying is the most important drying technique for fruit and vegetables. Food solar drying processes can be optimized not only in terms of dryer thermal performance, drying air uniformity, drying time or energy consumption, but also to attain the best dried product quality attributes. Reports indicated that drying at high temperatures and long drying times deteriorates the quality of the product, specifically its color, flavor, and nutrients (Praveen Kumar et al., 2006). Thus, the application of CFD modeling and simulation is very essential to find out the optimum drying temperature and time to minimize such product quality deteriorations. Pretreatments using chemicals such as dipping and blanching with sulfite and other solutions before solar drying commenced can minimize the loss of colors and vitamins while solar drying (Sablani, 2006). The important quality attributes could be predicted using the CFD model of the solar dryer by describing the quality kinetics using quantifiable variables (such as time, temperature, air velocity, and humidity) and coupling it to the model.

Defraeye and Radu, (2018) have been studied convective drying of apple fruit by coupled modeling to analyze quality evaluation and deformation (shrinkage) through quality evolution drying kinetics using CFD. The result indicated that quality attributes deteriorate at long drying time. The variation of a generic (heat-sensitive) quality attribute such as color loss, capsaicinoids, pungency, flavor, vitamin loss, enzymatic degradation during the drying process is estimated through a kinetic-rate-law model for the loss of these quality attributes.

The kinetic-rate-law model is widely used to determine the generic quality attribute (A) of fruits and vegetables in solar drying process as (Defraeye and Radu, 2018, Defraeye, 2016):

$$\frac{dA}{dt} = KA^n \quad (5.1)$$

where n is the order of the reaction, k is the rate constant [s^{-1}], and t is the time [s].

Solving this differential equation at a constant temperature results in a linear reduction (for zero order) or an exponential reduction (for first order) of the quality attribute over drying time as shown below:

$$A(t) = A_o - kt \quad (5.2)$$

$$A(t) = e^{-kt} + C \quad (5.3)$$

where C is an integration constant and A_0 is the quality attribute at the start of the drying process (t = 0 s). Fruit and vegetable quality decay depends on drying temperature and in this case, the rate constant k is expressed as a function of temperature in the form of an Arrhenius relationship as:

$$k\left(T\right)=k_{o}e^{-E_{A}/RT} \tag{5.4}$$

where E_A is the activation energy [J mol^{-1}], k_0 is a constant [s^{-1}], T is the absolute temperature [K] and R is the ideal gas constant (8.314 J mol^{-1} K^{-1}).

The important quality attributes of solar-dried vegetables and fruits, which can be considered during CFD modeling and simulations of solar dryer are discussed below.

5.1. Aflatoxin formation

The main source of microbiological and mycological growth is inadequate hygienic conditions during the solar drying process which can consequently result in the formation of mycotoxins (Hell et al., 2009) Most of mycotoxins are moderately heat stable in the range of 80 – 121 ^{o}C. Aflatoxins are one group of mycotoxins that require more serious attention, as they have even higher breakdown temperatures (237 - 306 ^{o}C) (Chiewchan et al., 2015). Aflatoxins are metabolites formed by certain fungal species of Aspergillus, i.e., A. flavus, A. parasiticus. Normally the warm and humid weather conditions are the conducive environment for the growth of these molds.

Short solar drying time of agricultural products is very important since it can avoid the favorable conditions for the growth of fungi. (Chiewchan et al., 2015). The solar drying process should be continued until the moisture is removed up to the minimum level without interruption and it is important to make sure that a solar dryer does not develop a conducive environment like high humidity that promotes microbial growth. For example, a solar dryer can develop a conducive environment to mold growth, especially at night in which solar energy is off. Even in a mechanical solar dryer (forced convection), when solar drying takes place at a lower temperature, there is a possibility that the dew point may be reached within the solar dryer, causing condensation over a product being dried which enhance the formation of aflatoxin. In this respect, thermal energy storage is very essential to provide energy during the night and off-sunshine hours which inhibits the favorable conditions for the growth of molds. Chiewchan et al. (2015) reviewed the application of solar drying technology to regulate aflatoxins in fruits and vegetables. Banout et al. (2011) examined the quality of chili during solar drying. The result indicated that the contamination by aflatoxin B1 was significantly lower in the chili that was dried using a solar dryer as compared to the traditional open-sun drying technique.

5.2. Chemical pretreatment

The importance of chemical pretreatment of fruit and vegetables before solar drying is to minimize enzymatic action, to improve flavor and color, to minimize nutrient loss, to stop decomposition by the microbes and to ensure even drying. Since the high temperature in the solar dryer deteriorates the quality of the produce, pre-treatments before solar drying like blanching, sulfuring, calcium chloride, and ascorbic acid are very important to avoid these quality losses (Mohamed and Hussein, 1994). The main purpose of blanching is to deactivate enzymes, reduce the solar drying time, and remove the intercellular air from the tissues. Sulphuring is done against the bacteria, molds, and to inhibit enzymatic browning, for the retention of oxidizable compounds like ascorbic acid. Reports indicated that Calcium chloride is a potential inhibitor of browning due to the chelation of calcium with the amino acids. Different reports showed that chemical pretreatment before solar drying has great importance on fruit and vegetable quality preservation. Chaethong et al. (2012) analyzed the color and quality characteristics of solar-dried chili and chili powder using metabisulfite as a pretreatment at different times and concentrations to reduce browning. Tunde-Akintunde and Ajala (2010) examined the effect of steam and water blanching and chemical soaking on the characteristics of solar-dried chili peppers. The result showed that pre-treatment highly affected drying rate and the pretreated pepper dried earlier than the untreated pepper. Other studies briefly showed the influence of chemical pretreatment during solar drying on the quality attributes of fruits and vegetables (Kumar et al., 2013, Belessiotis and Delyannis, 2011, Muyanja et al., 2014, Tadesse et al., 2015, Prajapati et al., 2011).

5.3. Color

Properties such as flavor, color, pungency, and different texture are the most essential quality attributes in most fruits and vegetables. The carotenoids are the important sources of color of fruits during the ripening stage (Topuz et al., 2009). For instance, the cause of red color is the carotenoid pigments such as Capsorubin, β-Carotene, capsanthin, lutein and they are mainly pro-vitamin A. Several factors such as moisture content, cultivar, maturity, and drying conditions are the most important parameter that influences fruit color value (Howard et al., 1994, Vega-Gálvez et al., 2009). The important source of pungency of fruit is capsaicinoids (Wesołowska et al., 2011). Furthermore, fruit and vegetables are an exceptional source of antioxidant polyphenols, particularly flavonoids, quercetin, and luteolin. In addition to the antioxidant properties of phenolics, they can be also used as hydrogen donors, metal chelators, reducing agents and oxygen quenchers (Vega-Gálvez et al., 2009). It has been reported that one color-related problem that is always come across during solar drying and long term storage of dried fruits and vegetables is browning (Maskan et al., 2002). The fruit color becomes decolorized at less than 10% moisture content, and at greater than 10% moisture content, there is a darkening possibility caused by non-enzymatic browning. Color retention of the fruit and vegetable during storage is greatly affected by temperature followed by moisture content. Therefore, in solar drying, the optimum storage conditions of fruit color retentions should be investigated (Malchev et al., 1982). In general, longer solar drying times and higher solar drying temperatures produce greater pigment losses. Ng et al. (2018) examined the main advantage of solar drying as well as heat pump supported solar drying for the preservation of flavonoid, color, and water activity of clinacanthus nutans lindau leave. The result showed that the darkening of leaves only happened at prolonged drying time and high drying temperature.

5.4. Flavor

Flavor depends on the aroma and taste of different fruits and vegetable products. During solar drying, flavor content increased in the leftover mass as moisture content is reduced (UNIDO, 2006). However, solar drying always reduces original volatile flavor contents while bringing extra volatile flavor content through autoxidation of unsaturated fatty acids and thermal degradation, or due to Maillard reaction initiation (Goff and Klee, 2006). Thus, appropriate control of solar drying conditions during each stage of drying minimizes these flavor losses.

6. Conclusion and recommendation

Drying technology has a significant role for fruit and vegetable preservation and post-harvest loss minimization in developing countries. Fruits and vegetables are important sources of digestible carbohydrates, minerals, antioxidants, fiber, and vitamins, and are a good source of income for the farmers as well as their country. However, fruits and vegetables are highly perishable and need appropriate preservation mechanisms to extend their storage and shelf life. It has been reported that the postharvest losses of fruits and vegetables in developing countries are as high as 40%. One of the recommended preservation techniques is the solar drying of the produces. To get the best out of the solar drying operation, it is essential to improve the drying conditions, dryer design, and product quality. In this study, the current progress of solar drying of fruits and vegetables, focusing on drying rate, drying time, quality attributes, and CFD modeling approach was reviewed to get a clear understanding of the design and performance of fruit and vegetable solar dryers. Several mathematical models have been used in studying fruit and vegetable solar drying operations and due to its simplicity, lumped parameter models are the easiest way. CFD modeling technique is the best option to get the spatial and temporal details of airflow, RH, temperature, and moisture distributions of the solar dryer. Short time drying, uniform drying air velocity, and temperature distribution in the drying chamber are the critical parameters in the solar drying process. To get this uniformity, CFD modeling played a major role and can be used to screen out the optimum drying conditions and dryer design. To screen out the optimum solar drying conditions and operation procedure, CFD modeling could integrate the product quality to the airflow, mass, and heat transfer properties of the solar drying operations. The quality of vegetables and fruit is the most important parameter in solar drying operations and it is mostly affected by the drying technique and drying conditions. For instance, to overcome the overheated product from solar dryer, which results in quality deterioration, chemical pretreatment is also a very essential parameter to preserve quality attributes during solar drying.

This review indicated that there were extensive CFD modeling and simulation studies on fruits and vegetables using conventional methods. However, there was limited research output regarding the CFD modeling and simulation of solar dryers in terms of hydrodynamic and thermal transport phenomena that explain explicitly the solar drying performance in terms of dried food quality. Thus, CFD modeling and simulation of the solar dryer is one of the future research areas specifically on the development of a model that is capable of predicting the product quality in relation to the drying conditions such as the airflow, heat, and mass transfer characteristics of the solar dryer. There is also a diverse recommendation on the type of solar dryer that should be utilized for the drying of fruit and vegetable products, and CFD modeling can be applied to select the optimum solar dryer for the drying of fruit and vegetable products. With a comprehensive summary of the existing numerous CFD modeling and simulation on solar drying, this review highlights the importance of CFD modeling in solar drying of fruits and vegetables to minimize postharvest loss and maximize dried product quality. In addition, this work clearly shows types of conventional solar drying systems, recent reports on CFD modeling of solar dryers, quality attributes, and main limitation of existing CFD modeling and simulation on solar drying of food products, and future research requirements on drying performance such as drying rate, kinetics and quality of food modeling using CFD.

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