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Review of industrial drying of fruits and vegetables

Industrielles Trocknen von Obst und Gemüse

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Summary

Fruits and vegetables are perishable in nature and need to be preserved to reduce post-harvest losses. To preserve fruits and vegetables for a longer time, drying is one of the most important and essential technique. It increases shelf life by preventing the microbial spoilage and reduction in bulk which significantly decreases the handling and storage cost. Traditionally, the perishable food items were dried in the open under the sun with the aim of preservation only without considering the quality of the product. But with the advancement of technology and increases awareness on food safety and quality, the emphasis took a shift with focus on various characteristics such as flavor, texture, functionality and nutrient value of dried product along with preservation. Various drying methods have been developed over time that is used for the drying of fruits and vegetables to get a wide range of dried products. An appropriate selection of the drying method is essential for the removal of moisture content. The development of drying technology divided into four generations from conventional to novel drying methods. In each generation, several dryers along with their operating principles, applications, advantages and disadvantages are reviewed. This paper focuses on the industrial application of each dryer for drying of various types of fruits and vegetables.

Keywords: Drying methods, fruits, vegetables, solar dryer, commercial dryers

Introduction

Fruits and vegetables are the richest sources of nutrient that keep the body healthy and help to prevent various diseases such as eye disease, cancer and cardiovascular disease (Mostafidi et al., 2020). Fresh produce has a high amount of both bound and unbound water, and thus perishable in nature. The poor processing methods and lack of storage facilities deteriorate the quality and quantity of agricultural produce especially fruits and vegetables. In India, 18% of fruits and vegetable production, valued at Rs 13,300 crore is wasted every year (Reddy, 2015) and mere 2.2% fruits and vegetables are processed even though the country ranks second in the world in terms of production. The use of various preservation methods is necessary to increase the shelf life and reduce the wastage of agricultural produce, cost of disposal and environmental problem. Improper handling causes mechanical and physical damage which further enhances microbial and chemical damage, hence, results in the spoilage of the produce. The most common cause of spoilage is due to chemical and microbial damage (Rahman, 1999; Mujumdar, 2004). The high moisture content of the product and poor storage conditions results in microbial spoilage. During storage, many chemical and enzymatic changes like browning occur which causes degradation of quality and food becomes unacceptable for consumption. Various techniques are used in the food industry to reduce the wastage of fruits and vegetables and increases their shelf life while maintaining the desired level of nutritional properties for the longest possible time and make them available for the lean season also. In the food industry, there are different techniques for preservation of fresh fruits and vegetables such as canning, refrigeration, freezing, vacuum packaging, food irradiation, drying, etc. Among these techniques, drying is one of the oldest and cheapest methods for preservation of fruits and vegetables. Although drying will never replace freezing and canning because these methods retain natural color, taste, texture and nutrient properties to a higher extent. However, drying is a better way for preserving fruits and vegetables as it adds variety to the product and the dried product require less storage space and efforts than that of the canned and frozen product.

Drying is widely used and is one of the cost-effective methods for preservation of fruits and vegetable that involves the removal of water by application of heat. It is a complex operation for removal of moisture from the product involving a couple of heat and mass transfer (Onwude et al., 2016a; Erbay and Icier, 2010; Onwude et al., 2017). Drying improves postharvest handling and packaging, increases the ease of product transportation and improves other processing operations such as mixing (Mujumdar and Law, 2010). Conventionally, the fruits and vegetables are dried in the sun which is a free and renewable source of energy. Due to various drawbacks of sun drying, the advanced system of sun-drying; solar dryers have been developed in which material is dried in a closed system with high inside temperature (Rajkuamr, 2007). Traditionally, in thermal processing of fruits and vegetables, main stress has been given on preservation and microbial safety with least emphases on nutrient content. The nutrients (vitamins, minerals) and bioactive compounds (phenolics) are lost during drying, which results in the lower nutritional value of the dried products. The activity and bioavailability of these compounds decrease as a result of physical, chemical and biochemical changes that take place during drying (Nicoli et al., 1999; Kwok et al., 2004; Chang et al., 2006; Lutz et al., 2011). The quality of the final product can be improved by controlled drying (Simal et al., 2000). Hence, to achieve best quality product many technologies like hot air drying (Ratti, 2001; Onwaude et al., 2016b), freeze-drying (Vergeldt et al., 2014), vacuum drying (Akbudak and Akbudak, 2013), etc. have been developed. Several novel techniques for drying of fruits and vegetables have been developed recently (Bonafonte et al., 2002; Mongpraneet et al., 2002; Chong et al., 2013; Aktas et al., 2016). The current trend in food industries is the development of novel drying technologies for improving the efficiency and efficacy of drying to reduce the energy consumption while at the same time preserving the quality of the final dried product (Mujumdar, 2002; Moses, et al., 2014). A significant number of studies are available on the drying of various fruits and vegetables by different conventional and novel methods but less aggregate information regarding the use of drying techniques at a commercial level. This review paper aims to highlight the various methods of drying; from conventional to novel non-thermal drying of fruits and vegetables with an emphasis on the impact of drying parameters on quality attributes of dried product.

Selection and classification of dryer

In food processing industries, selection of dryer is based on the manufacturing process. The selection of dryer for fruits and vegetable drying is more critical as it depends on several factors: type and cost of raw material, capital and operational cost and desired final product characteristics. The use of an expensive technique is not recommended for low-value food products. Hence, it is necessary to analyze the steps involved in the selection of dryer for a particular food product. The final decision for dryer selection should include various factors like production capacity, initial moisture content, particle size distribution, drying characteristics, maximum allowable product temperature, explosion characteristics, and physical data of the material (Humberto et al., 2001). Based on certain properties and characteristics, dryers are classified into various classes (Jangam and Mujumdar, 2010):

- Mode of operation – batch and continuous dryers
- Heat input type – convection, conduction, radiation, electromagnetic field, a combination of heat transfer modes, intermittent or continuous, adiabatic or non-adiabatic
- State of material in a dryer – stationary, moving, agitated and dispersed
- Operating system – vacuum and atmospheric
- Drying medium (convection) – air, superheated steam and flue gases
- Drying temperature – below boiling temperature, above boiling temperature and below freezing point
- Relative motion between drying medium and drying solids – co-current, counter-current and mixed flow
- Number of stages – single and multi-stage
- Residence time – short (< 1 minute), medium (1–60 minutes) and long (> 60 minutes) (Van't Land, 1991; Mujumdar, 1995; Mujumdar, 2008)

Drying Methods

Drying technology has evolved from the use of solar energy to various innovative techniques that are presently used at the commercial level. The development of dehydration technology can be divided into four groups or generations (Veg-Mercado et al., 2001) as shown in Table 1.

TABLE 1: Classification of dryers used in industries.

Generation	Type
First Generation Dryer	Cabinet and bed type dryer (kiln dryer, tray, rotary flow, conveyor, tunnel)
Second Generation Dryer	Spray dryer and drum dryer
Third Generation Dryer	Freeze drying and osmotic drying
Fourth Generation Dryer	High Vacuum, microwave, radiofrequency, refractance window

Solar Dryer

In Solar dryer, an appliance transmits heat from heat source (solar energy) to a product and remove moisture from the product surface to the surrounding air (Chauhan et al., 2015). The yield of the final product depends on the intensity of solar radiation; the most important factor in drying (Fudholi et al., 2014). Solar dryer saves energy and occupies less space. Moreover, it protects the environment by not releasing carbon monoxide, carbon dioxide, oxides of nitrogen and other smokes. It enhances the stability of the product, minimize the packaging problems and reduces weight and transportation cost (Chandramohan, 2016). The solar drying technique is widely used for industrial drying processes (Kumar et al., 2016). Fruits such as grapes, apples, pineapples, banana, dates, beets, mangoes, etc. and vegetables like tomatoes, onions, potatoes, carrots, etc., are preserved through solar drying (Prasad and Mullick, 1983).

Solar energy for drying of fruits and vegetables has not been widely commercialized due to huge investment, limited time and intensity of incident radiation, low skilled manpower for drying operation and poor maintenance of equipment. A variety of solar dryers have been developed for drying of different types of materials; classified as direct, indirect and hybrid on basis of mode of drying.

1. Direct Solar Dryer

The direct solar dryer is composed of insulated drying chamber, covered with a transparent cover made of glass or plastic and has holes to allow air to enter and exit the chamber (Ghazanfari et al., 2003; Seveda and Jhahjaria, 2012). When solar radiation impinges on the glass cover, a part is reflected in the atmosphere while the remaining part is transmitted inside the drying chamber. The transmitted part of the radiation is absorbed by the product surface leads to an increase in temperature of the product and thereby emits long wavelength radiations that are not escaped to the atmosphere due to glass cover (Sharma et al., 2009).

The direct solar dryer has a simple and easy construction, inexpensive and requires low maintenance cost. However, this dryer has a low drying rate that depends on climate conditions. Moreover, it also requires a large area and the quality of product deteriorates as a result of direct exposure to solar radiation (Sontakke and Salve, 2015).

2. Indirect Solar dryer

Indirect solar dryers have separate drying unit and solar collector, comprises a fan and a duct for air circulation (Green and Schwarz, 2001). The product is placed on the trays inside the drying chamber and solar collector heats the air entering the chamber. The warm air enters the drying chamber by the fan, transfers heat to the product and evaporate moisture from it.

The indirect solar dryer is more efficient as compared to direct type, as it has a high drying rate and can be operated at a higher temperature. Besides air velocity, dryer temperature and solid loading can be controlled (Kapadiya and Desai, 2014). It provides the required temperature, better control on drying, retention of product color, nil damage to crops and is highly recommended for photosensitive material such as lemon, cucumber, papaya etc. (Lingayat et al., 2020) and preserves the quality of the product by preventing direct exposure to the sun. However, this dryer has high capital and maintenance cost as compared to the direct type (Phadke et al., 2015).

3. Hybrid Solar Dryer

The hybrid solar dryer combines solar energy with another source of energy such as electricity, biomass, fuel, etc. The combined action of incident solar radiation and preheated air by auxiliary energy source produces the desired amount of heat required for the drying process. The hybrid solar dryers are expensive as they are fuel depended.

The modern solar drying equipment uses optimum energy and time and occupies less area for the production of superior quality products with almost zero energy cost (Prakash and Kumar, 2014). The greenhouse solar dryer has various advantages over other types which makes it a good alternative (Janjai et al., 2007). The greenhouse solar dryer not only reduces the consumption of fossil fuels for drying purpose but also provide the best quality dried product in terms of color and taste (Patil and Gawande, 2016). The working of greenhouse dryer is based on the principle of the greenhouse effect. The dryers operate in either passive (natural convection) or active mode (forced convection) (Nayak and Tiwari, 2008). The operation of a solar collector is combined with a greenhouse system. The walls and roofs of the dryer are manufactured from a transparent material such as glass, fiberglass, UV stabilized plastic or polycarbonate sheets (Toshniwal and Karale, 2013). To enhance the absorption of solar radiation, a black surface is required. Such type of dryer has a considerable drying control as compared to other types.

Various modifications and researches have been done to improve the performance of greenhouse dryer. Some modifications implemented on active and passive greenhouse soar dryers in literature are:

- PV integrated greenhouse solar dryer (Janjai et al., 2007; Nayak and Tiwari, 2008; Janjai et al., 2009; Ganguly et al., 2010; Prakash and Kumar, 2014)
- Use of opaque northern wall for insulation and prevention of heat loss (Sevda and Rathore, 2010; Prakash and Kumar, 2014; Chauhan and Kumar, 2017)
- Use of thermal storage material such as sand, rock-bed, black painted concrete floor and PVC sheet to make use of greenhouse during off sun-shine period (Janjai et al., 2007; Sevda and Rathore, 2010; Belloulid et al., 2017)
- Inclination and reflection of the north wall to collect maximum radiations (Seti and Arora, 2009)
- Using greenhouse coupled with solar air heater to achieve faster drying (Chan et al., 2015; Azaizia et al., 2017)
- Provide an additional area for panels enhancing to increase drying area (Jitjack et al., 2016)

First Generation Dryer

First-generation dryers include Cabinet and Bed Type dryers (kiln dryer, tray, rotary flow, conveyor, and tunnel) in which drying takes place in an enclosed chamber where hot air is flowing over the material to remove water from the surface. The rate of drying is influenced by various factors such as temperature, humidity, air velocity and distribution pattern, geometry, characteristics and thickness of the product.

Cabinet dryers are small scale dryers used in laboratories for experimental drying of fruits and vegetables. The drying takes place in an insulated chamber where food is placed and the hot air is allowed to pass over the product (Barbosa- Canovas and Vega- Mercado, 1996). The material is dried in batches and mostly used for low-value products. In the tray dryer, the food to be dried is placed in the trays which are stacked one above the other in an insulated drying chamber. To obtain the uniform quality of the product, the uniformity of airflow over the trays is crucial. A poor airflow distribution causes variation in the final moisture content of the dried product placed at different trays in the dryer. Tunnel dryers are considered as a development of tray dryers. Food is loaded in trays on trolleys which move through a tunnel where the heat is applied and the moisture is removed. In most cases, hot air is used for drying and the material can move through the dryer either parallel or opposite to the airflow. The drying capacity of dryer depends on the size of the tunnel, number of trays, drying temperature and airflow rate. This dryer produce uniform drying and re-circulated air can be used that is heated by a conventional burner.

In continuous conveyor dryer, food is dried on a mesh belt in a deep bed. The wet material is loaded on the surface of a slow-moving conveyor belt and spreads evenly in a relatively deep layer. The hot air initially directed upwards through the bed of food and then downwards for prevention of light-weight nearly dried pieces from blowing out of the bed. The uniformity in the drying of material can be improved by designing the dryer to produce up-through and down-through flow in alternate sections. Depending on the material to be dried, this type of dryer is capable for drying a product with the water content of 80-90 % down to 5 % on a wet basis (wb) in a single pass at a feed rate of 2-7 metric tons per hour. Although relatively expensive, the dryer can produce a consistent dried product with higher throughput capacity as compared to a cabinet or tunnel dryer (Tang and Yang, 2003).

Rotary dryer is made up of a cylindrical shell which is rotating around its axis. Material to be dried is fed to the dryer and with the rotation of dryer, the material is lifted by a series of internal fins lining the inner wall of the dryer. When the material falls to the bottom of the dryer, it passes through the hot gas stream. The flow of this gas stream can either be co-current or counter-current. The shell is slightly inclined horizontally which facilitate the flow of material. A large surface area of food is exposed to the hot air stream which facilitates high drying rates and the uniformly dried product. On basis of configuration, rotary dryers can be classified as co-current, counter-current, direct fired and indirect fired. Counter-current dryers are used for heat-sensitive material as it gives a better result and higher drying rate (Mujumdar, 2004). Industrial rotary dryers have a shell diameter, length and inclination in the range 0.3-3 m, 1.2-30 m and 0-4°, respectively. The shell rotates at 4-8 rpm, the drying air temperature is 121-288°C and velocity of air mass in the dryer is in range of 0.5-5 kg/s.m2 (Moyers and Baldwin, 1997; Mujumdar, 2004).

Second Generation Dryer

Second generation dryers are mainly used for dehydration of purees and slurries. These include spray dryer and drum dryer; meant for dehydrated powder and flakes. At a commercial level, drum dryers are used for the production of powdered or flaked ingredients. In drum dryers, an indirect heat conducts through a solid surface. The material (liquid, slurry or puree) to be dried is applied as a thin layer over the surface of revolving drums that are heated internally by steam. The drum drying is one of the most energy-efficient drying methods and is most effective for drying of high viscous liquid or puree. Drum dryers are classified into single drum dryer, double drum dryer and twin drum dryer. Single and double drum dryers are commonly used for drying of fruits and vegetables. The single drum dryer is used for producing large quantities of mashed potato flakes whereas double drum dryer is used to dry tomato paste. Twin drum dryer is used only for drying material yielding dusty products.

The heat-sensitive material can be dried using a vacuum dryer. In the vacuum dryer, the drums are enclosed in a vacuum chamber which reduces the drying temperature (Qui et al., 2018). Vacuum dryer equipment and operations are expensive, therefore, used for the production of high-value products or products that cannot be produced more economically by other means. The products obtained from the drum drying method have good porosity and rehydration properties. This method is used for drying of viscous foods (like pastes and gelatinized or cooked starch) which cannot be easily dried with other methods.

Spray drying is single-step processing in which liquid feed or slurry is transformed into dry powder by using hot air. This method is preferred for heat-sensitive material. The spray dryers use an atomizer or spray nozzles to disperse the liquid slurry into smaller droplets to increase the surface area. When dispersed droplets come in the contact with drying medium (hot air), the moisture evaporates. The hot air can be passed as co-current or counter-current to atomizer depends upon the type of dryer. Such operating conditions increase product recovery and superior quality product is obtained. Product recovery is specified by the efficiency of powder collection (Goula and Adamopoulos, 2005). The fruits and vegetables which have been dried by spray drying method are banana, orange, bayberry, mango, apricot, blackcurrant, raspberry, ginger, guava, lime, pineapple, tomato, watermelon, etc. Most of these comprise of different carbohydrates such as monosaccharides (glucose, fructose), disaccharides (sucrose) and polysaccharides (Dolinsky and Gurov, 1986) that stick to the dryer wall, thus, leads to operational problems. The problem of stickiness is caused by high hygroscopicity, high solubility, low melting point temperature and low glass transition temperature (Tg) of sugar-rich feed (Masters, 1991). The stickiness of powder can be prevented by various methods such as the addition of drying agent material, improvement in drier design (Papadakis and Babu, 1992; Chegini and Ghobadian, 2005), scrapping of dryer surfaces (Karatas and Esin,1994), cooling of chamber wall lower than the Tg of powder (Chengini and Ghobadian, 2005; Chegini et al., 2008) and entering the atmospheric air near the bottom of the chamber allows the transport of powder to a collector having a low humidity atmosphere (Ponting et al., 1973).

Masters (1991) has explained the advantages of spray drying technology. It is a continuous and easy drying operation and adaptable to full automatic control. The particle size of the spray-dried food product remains constant throughout the dryer if drying conditions are held constant. A wide range of dryer designs is available that are used for heat-sensitive, heat-resistant materials, corrosives and abrasives.

Third Generation Dryer

This generation includes freeze-drying and osmotic dehydration. The high processing temperature of traditional drying methods deteriorates the organoleptic properties of fruits and vegetables. To overcome this issue, the freeze-drying system has been developed (Karel, 1975; Dalgleish, 1990). In freeze-drying, the water is removed from the product by sublimation method (Di Matteo et al., 2003) which is achieved by lowering the temperature and pressure under the triple point of water (Dilta et al., 2011). The low temperature prevents undesirable shrinkage and the dried material has high porosity, unchanged nutritional quality, better taste, aroma, flavor and color retention as well as better rehydration properties (George and Datta, 2002).

The freeze-dried berries retain the antioxidant properties of the raw material better as compared to air-dried material (Michalczyk et al., 2009). The freeze-dried strawberries had better nutritional content and good rehydration capacity (Meda and Ratti, 2005). Hung and Duy (2012) found that the total phenolic and flavonoid content in freeze-dried vegetables like carrot, taro, tomato, red beetroot and eggplant were significantly higher than that of conventionally heat-dried vegetable. Blueberries dried by freeze-drying method had the highest retention of important components, soluble solids and color as compared to blueberries dried by other methods of dehydration (Yang and Atallah, 1985).

There are certain limitations of freeze-drying. The food whose structure is susceptible to damage during freezing will have a poor structure upon rehydration (Krokida et al., 1998). The proteins can be denatured during the freezing stage of drying due to solute concentration. Freeze-dried foods are prone to oxidation during storage. Being brittle, the freeze-dried product is susceptible to mechanical damage. To overcome this problem, expensive packaging may be required.

Freeze drying consumes a large amount of energy because of its long operational time; makes it expensive process as compared to air drying process which removes water in a single stage (Marques et al., 2006; Wu et al., 2019 a,b). On an industrial scale, the running cost of the freeze-drying process is four to five times higher than that of spray drying technique and eight to ten times higher than that of the single-stage evaporator (Flink, 1977). For this reason, freeze-drying is not used for the drying of fruits and vegetables at industrial scale (Shishehgarha et al., 2002).

In recent years, osmotic dehydration (OD) has received greater attention. It is an effective method for drying of fruits and vegetables like banana, mango, pineapple, sapota and leafy vegetables, etc. with retention of initial characteristics such as color, aroma and nutritional compounds of fruits and vegetables (Chavan and Amarowicz, 2012). In this method, dehydration of fruit slices takes place in two stages; firstly, water is removed by using an osmotic agent, then moisture content is further reduced in a dryer to make the product shelf-stable (Ponting et al., 1973). Osmotic dehydration also called a – Dewatering Impregnation Soaking Process (DISP), a water removal technique which is mainly applied to horticultural products (fruits and vegetables) to reduce the water content while increasing soluble content (Kaymak-Ertekin and Sultanoglu, 2000). The fruits and vegetables are processed by immersing in a hypertonic solution (Raoult- Wack et al., 1989). OD system consists of a storage tank in which the osmotic solution is prepared and a pump to control the flow rate in the processing tank. The product is placed in a processing tank where the osmotic solution is pumped in at a constant rate. The raw material is immersed in concentrated solution (salts, alcohols, starch solutions and concentrated sugars) of high soluble solids with higher osmotic pressure and lower water activity. When food material is immersed into an osmotic solution, water outflows from the food tissue into the osmotic solution along with leaching out solutes (sugars, organic acids, vitamins, minerals) of the food tissues. The transfer of a solute from food material to the osmotic solution is negligible as compared to the composition of the product (Akbarian et al., 2013).

For dehydration of diced potato, NaCl with sucrose is used (Lenart and Flink, 1984a,b) and NaCl and ethanol in water are used for dehydration of diced carrots (Le Maguer and Biswal, 1988). The flavor of processed fruit is sweeter due to an increase in sugar content in concentrated fruit (Pointing et al., 1973; Sankat et al., 1996). The osmotic food processing results in substantial-quality and considerable economic benefits as compared to other processes (Matsuka et al., 2006).

High-temperature short drying time is possible for OD of low moisture product. Osmosed products should be processed (dried, pasteurized, or frozen) further (Pointing, 1973; Sankat et al., 1996). The osmo-dried papaya and mango slices were dried in a cabinet dryer for 6 hr at 60°C to obtain 16% moisture content (Gurumeenakshi et al., 2005). OD is used as a pretreatment to many processes as it improves nutritional, sensorial and functional properties of food without changing its integrity (Chandra and Kumari, 2015). It is effective even at ambient temperature, resulting in the reduction of damage to texture, color and flavor of food due to heat (Rastogi and Raghavarao, 1997). It is an energy-efficient technique as compared to other dehydration techniques like air, vacuum and tray drying due to processing at low or ambient temperature. It inhibits polyphenol oxidases activity and prevents enzymatic browning. Osmo-dried products are more stable during storage than unprocessed fruits and vegetables due to low water activity by sugar gain and water loss that reduced chemical reactions and growth of toxin-producing micro-organisms in food (Akbarian et al., 2013). The volume of the product reduces thereby saving the processing, storage and transport cost. OD protects against the structural collapse of the product during drying hence, the shape of dehydrated products retained. Despite various benefits, Falade and Igebeka (2007) reported a few demerits. The industrial application of process faces engineering problems related to the movement of large volumes of concentrated sugar solution and in the design of equipment for continuous operation. Solute uptake and leaching of the valuable product takes place which imparts negative impact on sensory characteristics and nutritional profile.

Fourth Generation Dryers

Use of high vacuum, microwave, radiofrequency, refractance window drying represents the latest advancements in this area of food processing. Each of these technologies has a specific application based on the quality attributes of the final product as well as physical/ chemical characteristics of the raw material being processed (Humberto et al., 2001).

In vacuum drying, lowering the ambient pressure creates a higher pressure difference, a primary driving force for moisture transfer. The larger the pressure difference, the faster the rate of drying (Chen and Lamb, 2007). In industries, vacuum drying is used in conjunction with other drying techniques like vacuum freeze drying, vacuum microwave drying that improves the quality of dehydrated products. The low temperature and fast mass transfer conferred by vacuum (Yongsawatdigul and Gunasekaran, 1996a) combined with rapid energy transfer by microwave heating, causes fast drying at low temperature. The vacuum during drying also inhibits the oxidation, results in the preservation of color and nutrient content of the dried product. Vacuum microwave dried cranberries had redder color and softer texture as compared to hot air-dried cranberries (Yongsawatdigul and Gunasekaran, 1996b). The vitamin A, vitamin C, thiamin, riboflavin and niacin content in dried grapes were largely preserved during microwave vacuum drying (Petrucci and Clary, 1989). The texture of food materials may be modified by microwave vacuum drying (MWVD). The MWVD was applied to apple slices to remove internal free water following by the freeze-drying to dry the product below 7% moisture with higher retention of vitamin C as compared with hot air drying (Cui et al., 2008). Huang et al., (2009) found that freeze-drying of apple slices for 6 hours followed by MWVD results in the final dried product with the acceptable appearance and highest energy savings.

In the food industry, microwave (MW) is mainly used for drying of fruits and vegetables as it shortens the drying time and improves the final quality of the dried product. As per international regulations, microwave frequencies 2450 MHz and 915 MHz are used for industrial application. During MW drying, the heating period is relatively short and moisture loss is small (Bouraoui et al., 1994). Dielectric heating with MW energy has found industrial application in the drying of food products like fruits and vegetables. The advantages of MW drying come up from the volumetric heating and internal vapor generation. Internal vapor pressure is build up by heating the interior of the food that drives the moisture out of the product thus, reduces drying time (Schubert and Regie, 2006). In microwave drying of food, drying time is reduced up to 25-90% (Feng et al., 1999; Maskan, 2001a) and drying rate increases 4-8 times (Brygidyr et al., 1977; Chen and Pei, 1989) when compared to convective drying technique. Other advantages of microwave drying include:

1. Due to surface moisture accumulation and liquid pumping phenomena, case hardening may be avoided or lessened. In MW heating, surface moisture accumulation has been widely reported (Turner et al., 1998; Ni et al., 1999).
2. An improvement in the quality of the final product can also be achieved. For MW dried food products, better aroma retention (Feng et al., 1999), faster and better rehydration (Drouzas and Schubert, 1996), better color retention (Feng and Tang, 1998) and higher porosity (Torringa et al., 1996) have been reported.

MW drying alone has many drawbacks like uneven heating, overheating, textural damage and limited penetration of MW radiation in the product. In MW drying, a too rapid mass transfer takes place which may cause quality damage or undesirable changes in the food texture by 'puffing' (Nijhuis et al., 1998). Therefore, other techniques are combined (Fig. 1) to overcome these drawbacks.

Microwave-assisted Air Drying (MWAD)

MWAD is used to shorten the drying time and improve food quality (Schiffmann, 1992). Many research reports focus on drying of fruits and vegetables including apple, potato, carrot, kiwifruit, olive, grape, orange slices and asparagus. However, the industrial application of this drying technique is limited. MW energy is combined with hot air drying by applying MW energy at the beginning of dehydration process when the drying rate begins to fall; and in the falling rate period (Andres et al., 2004).

MW-assisted drying techniques are divided into two categories: MW-assisted drying in the whole air-drying process (MDWAD) and MW-assisted drying as the final stage of the air-drying process (MDFSAD). Funebo and Ohlsson (1998) described MW-assisted air dehydration of apple and mushroom. The drying time for apple and mushroom was reduced with MDWAD. A simulation study on combined convection and MW heating using potato and carrot was carried out by Jia et al. (2003) and found that up to a certain value of moisture diffusivity, the rate of drying increased with the increment of moisture diffusivity. For specific drying conditions, if the moisture diffusivity of product is higher than the threshold value, the drying rate remains unchanged. However, with volumetric heating using MW, moisture diffusivity of the product increases. Dehydration-rehydration of orange slices in combined MW/ air drying was modelled by Ruiz Diaz et al., (2003). In their study, a sharp reduction in the drying time of orange slices was obtained at low levels of MW power and no difference in rehydration behavior was perceived.

The vegetables and fruits having high moisture content require more time for drying in the final stage. When MW drying applied to the final stage of drying, a high thermal efficiency, shorter drying time and improvement in the quality of the product were observed (Xu et al, 2004). The drying time of banana slices reduced by about 64% by using MW finish drying and the product with a lighter color and higher rehydration value was obtained as compared to traditional airflow drying (Maskan, 2001b). Shrinkage of kiwifruits is not observed with MDFSAD which occurs during normal MW drying. Introduction of MW increased the rate of color deterioration and produced more brown products in kiwifruits (Maskan, 2001b). Some pretreatment before drying (e.g. osmotic dehydration in sucrose) may reduce the extent of discoloration.

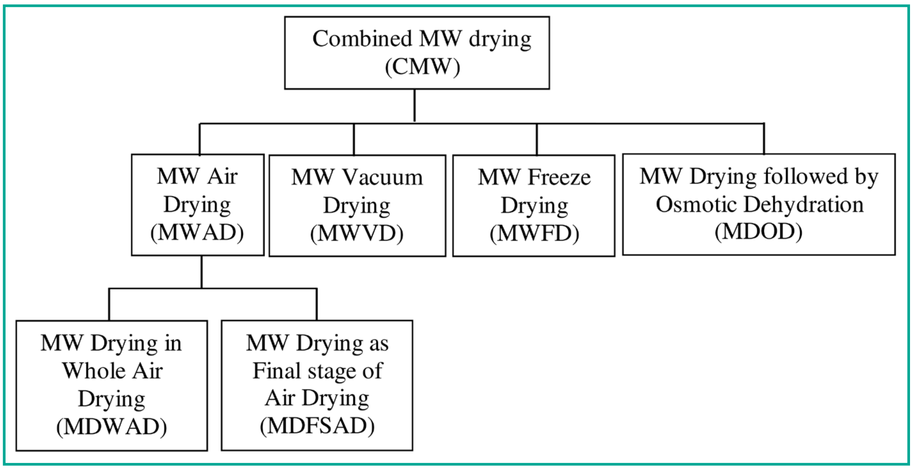

FIGURE 1: *Combined Microwave related Drying Application.*

MW-assisted vacuum drying (MWVD)

The deterioration of quality in conventional hot air drying can be prevented by a vacuum drying process in which high-energy water molecules diffuse to the surface of the product and evaporates due to low pressure. The vacuum in the drying chamber results in the reduction of water vapor concentration at the surrounding of the product. Also, it lowers the boiling point of water in the interior of the product. This creates a large vapor pressure gradient between the food interior and surface resulting in rapid drying rates. Thus, for a given drying rate, vacuum enables the product to dry at a lower temperature. It also reduces oxidation due to the absence of air. Because of these various advantages, the color, texture and flavor of dried products are improved (Gunasekaran, 1999). There is a need to maintain vacuum over a long period of drying thus, increases the operating cost. The vacuum drying in combination with MW has been investigated to speed up the process. Most MWVD studies focus on the 'puffing' quality of fruits and vegetables in the final product. MWVD are used successfully for the dehydration of grapes (Clary et al., 2005), cranberries (Yongsawatdigul and Gunasekaran, 1996a), bananas (Mousa and Farid, 2002), tomatoes (Durance and Wang, 2002), carrots, garlic (Cui et al., 2005), kiwifruit, apple and pear (Kiranoudis et al., 1997). These products have excellent quality in terms of taste, aroma, texture and appearance. Conventional drying and MWVD of lycopene-rich carrots were compared by Regier et al. (2005) and concluded that the drying time was shortened to less than 2 h by MWVD compared with 4.5-8.5 h in convectional drying with similar carotenoid stability (50-70°C). MWVD was compared with air drying and freeze-drying by Lin et al. (1998). MWVD sliced carrots had higher rehydration potential, higher α-carotene and vitamin C content, lower density and softer texture as compared to those prepared by air drying. Although freeze-dried carrot slices had improved rehydration potential, appearance and nutrient retention, the MWVD carrot slices were rated as equal to or better than freeze-dried samples by the sensory panel in terms of color, texture, flavor and overall preference in both dry and rehydrated states.

MW-assisted freeze-drying (MWFD)

Freeze drying is an expensive and time taking process because of low drying rates which lead to relatively small throughput, high capital and energy cost generated by refrigeration and vacuum system (Zhang and Xu, 2003). The use of freeze-drying on the industrial scale is restricted to high-value products due to high cost. Some of the above-mentioned disadvantages are overcome by MWFD as it has the characteristics of heating-up material volumetrically. In MWFD, drying rate was increased and drying cost reduced with MW heating (Wu et al., 2004). Many studies demonstrated that MWFD provided a 50-70% reduction in drying time as compared to conventional freeze-drying methods (Cohen and Yang, 1995). MWFD dried products showed higher volatile retention level than the conventional freeze-dried products. MWFD dried peas showed a higher rehydration capacity as compared to conventional methods.

MW-assisted finish drying following osmotic dehydration (MDOD)

Osmotic dehydration in combination with MW drying has been widely studied (Prothon et al., 2001). MW drying of osmotically dehydrated products has been shown to improve the drying rate and retain the quality as compared to air drying (Contreras et al., 2005). MDOD are tested for fruits and vegetables like apple (Funebo et al., 2002; Contreras et al., 2005), strawberries (Piotrowski et al., 2004), potato (Ahrne et al., 2003). Osmotic pretreatment before MW-assisted air drying increased the final overall quality of the product and firmness of the rehydrated apples (Prothon et al., 2001).

Radio Frequency Drying

Radio frequency (RF) electromagnetic waves for heating behavior cover the frequency range between 10 to 300 MHz and only three frequencies, 13.56 MHz ± 6.68 kHz, 27.12 MHz ± 160.00 kHz, and 40.68 MHz ± 20.00 kHz are allowed by the US Federal Communications Commission (FCC) to avoid interference with other communication systems (Wang et al., 2001). RF heating is also known as high-frequency dielectric heating. RF heating application in the food industry has been recognized since 1940s (McCormick, 1988; Anonymous, 1993). The first attempts were to use RF energy to cook processed meat, to heat bread and dehydrate vegetables (Moyer and Stotz, 1947; Kinn, 1947). The application of RF heating technology has not been adequately investigated. RF drying has an advantage over MW heating for large size food particles due to deeper penetration, more uniform heating and more stable product temperature control (Wang et al., 2014; Zhou et al., 2018). On the other hand, dielectric drying based on RF energy has high energy consumption and uneven heating (Zhou et al., 2018; Zhou and Wang, 2018). A combination of drying technologies is applied to develop fast and energy-saving process and to minimize the limitations of individual drying technologies (Hung et al., 2012). RF drying can be combined with other drying methods like hot air drying, vacuum drying and osmotic dehydration (Zhou et al., 2018).

Refractrance Window Drying

The Refractance Window (RW) drying is relatively a non-thermal development for drying heat-sensitive purees (Nindo et al., 2003a) and slices (Ochoa-Martinez et al., 2012) of fruits and vegetables. A moist material is applied on the surface of conveyor belt made of food-grade Mylar (transparent polyester film) floating on the surface of heated cistern containing circulating hot water (Baeghbali et al., 2010; Rostami et al., 2017). The infrared heat from the hot water is conducted by a way of a "refractance window", through the mylar belt to the water present in raw material laying. As the material travels down the conveyor, the water in the material evaporates through the "window" in a matter of moments, with the "window" closing in proportion to the rapid dissipation of water (Nindo et al., 2003a). The Mylar conveyor belt is a poor conductor of heat, once the material dries, the "refractance window" closes and a minuscule amount of heat is transferred to the product as it is carried to the end of the conveyor system. In the whole process, three modes of heat transfer (conduction, convection and radiation) occur. Raw material dried through RW process delivers a flaked product close to its natural state. RW drying operates at atmospheric pressure and the temperature of hot water is usually 95-97°C. The temperature of the product can reach up to 74°C (Castoldi et al., 2015) that are highly dependent on moisture content, bed thickness and product consistency. Products like juice, purees and suspensions are spread over the transparent plastic conveyor belt that moves over the hot water. Several fruits and vegetables like carrots, squash, asparagus, blueberries, strawberries, mangoes, etc. have been successfully dried by RW drying technique with good retention of quality parameters.

RW drying has become attractive for application in the food industry due to various benefits. It produces high quality dried product with reduced drying time (Raghavi et al., 2018). The cost of RW drying equipment is approximately one third to one half that of freeze dryer to dry a similar amount of product and energy costs to operate RW dryers are less than half of freeze dryers (Nindo and Tang, 2007).

Nutrient loss/retention during drying

The nutrients are lost during the drying process either due to applied heat or leaching through the water. Nutrients that are sensitive to heat, water and oxygen are degraded during drying. However, by applying suitable drying techniques, the nutrient loss can be minimized. A notable amount of nutrients are retained by selecting appropriate method and conditions for drying. Park (1987) reported a loss of 63% carotenoid content in carrots during m MW drying. Carotenoids are more sensitive to drying temperature than drying time (Mohamed and Hussein, 1994). Nindo et al. (2003b) assessed the effect of different drying technologies like tray drying, microwave drying, refractance window drying, and freeze-drying for retention of ascorbic acid in asparagus and found that the retention of ascorbic acid was higher with RW and FD. The effect of different drying methods and conditions on the nutritional content of fruits and vegetables are presented in Table 2.

It was reported that the retention of vitamins in freeze-dried material is significantly higher than that of the oven or sun-dried product. MW, refractance window and vacuum drying process also reduce the loss of vitamins due to a low level of oxygen. Shade drying, in the absence of light, can also be effective in retention of nutrient (Sablani, 2006).

Future trends in drying

Drying processes are widely used in the food industry for the production of a variety of products. The increased demand of the consumer for products with enhanced nutritional characteristics that improve the quality of life has forced industries to develop and optimize drying processes. Also, the need to reduce the energy consumption of several industrial processes promotes the need for research and development (R&D) to make the processes environmental friendly and reduce their environmental footprint. There is limited research on novel drying techniques for drying of fruits and vegetables. The interaction of industry with academic and their support is necessary for effective knowledge transfer. Academic researchers can help solve the real-time problems that industry faces, and at the same time industries can succeed by utilization of the research results. Newcomers to the multidisciplinary drying sector should offer innovative solutions to industries and satisfy their practical needs. Scientists and employees in the drying sector should give attention to the R&D to bring novel drying methods to industrial use for the production of products with superior quality.

Conclusion

In recent years, drying operations have made possible the production of various value-added and convenience food products from fruits and vegetables. A brief overview of the application of drying of fruit and vegetable at the industrial level is presented for both conventional and novel drying technologies. Among various technologies, osmotic dehydration, vacuum drying, freeze-drying, microwave drying and spray drying are offering great scope for production of best quality dried products and powders. Due to selective and volumetric heating effects, microwaves bring new characteristics such as increased rate of drying, enhanced final product quality and improved energy consumption. The quality of microwave dried fruits and vegetables is between air-dried and freeze-dried products. The rapidity of the process yields better color and aroma retention. Quality is further improved when the vacuum is used since the thermal and oxidative stress is reduced. Because of the high cost, using a single unit operation to dry the product is not cost-effective. Therefore, cost-effective alternate systems like combination/hybrid drying should be promoted to reap the advantage of sophisticated drying systems with minimum cost and simple technologies. However, several factors should be taken into consideration for developing a drying system for fruits and vegetables. Some emerging drying technologies like RW that will slowly replace traditional ones are also identified, but most of them still require significant R&D effort to be marketable. In this paper, we have focused on industrial applications of various drying technologies. Indeed, much R&D effort is needed in the area of fundamentals to develop more general theories of drying. Such effort should be carried out in academia in close cooperation with industry. Close industry-academia interaction will ensure rapid technology transfer and definition of appropriate research goals. We need appropriate R&D, not high-tech R&D, which may have only imaginary applications.

Conflict of interest

There is no conflict of interest.

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TABLE 2: Effect of different drying methods on nutritional content.

Product	Drying methods and conditions	Components	Observations/result	References
Spaghetti	Convection air (45 to 70 °C) relative humidity 95 % reduced to 65 %	Thiamine, riboflavin and niacin	▪ Loss of 16–28 % vitamin at high-temperature drying ▪ Storage study: no loss of thiamine, riboflavin, more susceptible to storage time and light (losses 22 % without light and 78 % with light), no loss of niacin during 3 months storage	Watanabe and Ciacco, 1990
Carrot (cubes: 1 cm^3)	Convection air 40, 50 and 60 °C; Pretreatment: Glycerol & $CaCl_2$ (control), Na metabisulfite, L-cysteine-HCl, acetyl cysteine	Ascorbic acid, carotenoid content	▪ L-Cysteine-HCl retained the highest content of ascorbic acid ▪ Ascorbic acid adversely affected by drying time, time, less by drying temperature ▪ Carotenoid content highest at low- drying temperature (40 °C) ▪ Na metabisulfite treatment was able to reduce oxidation of carotenoid	Mohamed and Hussein, 1994
Potato	Convection air drying temperature 40, 50, 60 °C, relative humidity 30 %	Ascorbic acid	▪ For given residual moisture content of the solid, nutrient loss increased with increase in drying air temperature and relative humidity, and a decrease in initial moisture content	Rovedo and Viollaz, 1998
Carrot (slices: (4 mm thick)	Vacuum microwave, air and freeze-drying with blanching	Carotene and vitamin C	▪ Total carotene loss was 19.2 % for air drying and 3.2 % with vacuum microwave drying; no significant loss with freeze-drying ▪ Retention of vitamin C was 38 % with air drying and 79 % with vacuum freeze-drying, no loss with freeze-drying ▪ Blanching reduced vitamin C by 38 %	Lin et al., 1998
Okra (whole)	Sun (33 °C), air (40, 60 and 80 °C), vacuum (600 mm Hg) drying; pretreatment: blanching with or without 0.2 % sodium metabisulfite	Ascorbic acid	▪ Retention varied from 25 to 44 % depending upon the condition ▪ Vacuum dehydrated samples retained more ascorbic acid ▪ High dehydration temperature had a negative effect on ascorbic acid retention ▪ Blanching in sulfite solution led to the retention of more ascorbic acid	Inyang and Ike, 1998
Potato (spheres: 22 mm dia)	Air drying (30, 45 and 60 °C)	Vitamin C	▪ Rate of vitamin loss increased with air temperature	McLaughlin and Magee, 1998
Tomato (whole, perforated with fine needles)	Air drying at 95 °C for 6–10 h; vacuum drying at 55 °C for 4–8 h; osmotic treatment at 25 °C in 65° Brix sucrose solution for 4 h, followed by vacuum drying at 55 °C for 4–8 h	Lycopene	▪ No loss of total lycopene content but the distribution of trans- and cis- isomers changed ▪ Osmotic treatment and vacuum drying was able to retain 94 % of all trans-isomers ▪ Air drying reduced the all trans-isomers by 17 %	Shi et al., 1999
Apple (12 slices from each apple) and strawberry (halves)	Osmotic pretreatment in sucrose solution (60 %) and microwave vacuum drying, strawberry 390 W for 37 min plus 195 W for 15 min, apples 390 W for 30 min plus 195 W for 39 min, pressure 5 kPa	Vitamin C	▪ No vitamin loss during osmotic drying ▪ Vitamin C retention was 60 % after microwave vacuum drying	Erle and Schubert, 2001
Strawberry (puree) and carrot (puree)	Freeze (33 kPa, 20 °C), drum (surface temperature 138 °C), spray (inlet 195, outlet 95 °C), and refractance window (air at 20 °C and 52 % relative humidity, air velocity 0.7 m/s, water temperature 95 °C, belt speed 0.45 to 0.58 m/s) drying	Ascorbic acid, ß-carotene	▪ Ascorbic acid retention in strawberry purees dried with RW system (93.6%) was comparable to freeze-dried products (94 %) ▪ Total carotene retention in carrot puree after RW drying (91.3 %) was comparable with freeze-dried (96.0 %) samples and much higher than in drum-dried (44 %) product	Abonya et al., 2001
Potato (slice: 30 x 30 mm and 15 mm thick)	Heat pump drying, temperature 20 to 35 °C and humidity, 0.0074 to 0.0103 kg/kg dry air	Vitamin C	▪ Cyclic air temperature in minimizing the loss of ascorbic acid over continuous temperature ▪ Square wave with 25 °C mean temperature showed 33 % improvement in ascorbic acid retention	Ho et al., 2002
Asparagus (slice: 2–4 mm thick)	Tray, spouted bed, combined microwave and spouted bed, refractance window and freeze-drying	Ascorbic acid	▪ Retention of ascorbic acid was higher with RW and freeze-drying ▪ Among the methods involving the use of heated air, microwave spouted bed drying at 2 W/g and 60 °C resulted in the highest retention of total ascorbic acid in asparagus	Nindo et al., 2003b
Tomato (pulp)	Spray drying; inlet temperature 110, 120, 130 and 140 °C, air flow rates 17.5, 19.25, 21.0 and 22.75 m^3/h	Lycopene	▪ Lycopene loss ranged from 8.1 to 20.9 % ▪ Loss was influenced by air temperature, feed rate, initial feed solid concentration, drying and compressed air flow rates	Goula and Adamo poulos, 2005

TABLE 2: ... continued

Product	Drying methods and conditions	Components	Observations/result	References
Indian gooseberry (puree)	Vacuum drying and low-pressure superheated steam drying	Ascorbic acid	■ In general, ascorbic acid and color retention was better with LPSSD; however, vacuum drying at 75 °C and absolute pressure of 7 kPa was best in retention of ascorbic acid ■ Drying condition did not influence retention of ascorbic acid with LPSSD ■ Temperature influenced the retention of ascorbic acid during vacuum drying	Methakhup et al., 2005
Carrot (slice: 1–6 mm height, 16–20 mm diameter)	Air (velocity 2.5 m/s, temperature 60 and 70 °C), inert gas (nitrogen, 50–90 °C, relative humidity 8 %), microwave vacuum (pressure 5 kPa, 400 and 600 W), and freeze (Condenser 60 °C, plate 30 °C and pressure 6Pa) drying	Carotene, lycopene	■ Temperature below 70 °C retained more carotene ■ No advantages of stability of carotene during drying in nitrogen environment ■ Complete retention of carotene during freeze-drying	Regier et al., 2005
Carrot (cube: 1 cm^3)	Low-pressure superheated steam drying (LPSSD) (7 kPa, 20 k/h, fan speed 1100 rpm), vacuum drying and air drying, temperature of 60, 70 and 80 °C used in all three methods	Carotene	■ Loss of carotene of 20–25 % with LPSSD and vacuum drying ■ Loss of carotene was less with LPSSD and vacuum drying compared to hot air drying ■ The influence of temperature on retention of carotene was more pronounced with LPSSD and vacuum drying	Suvarnakuta et al, 2005
Okra slices	Hot air drying at a constant velocity of 1 m/s and temperature in the range of 40–90 °C	Color, texture and taste	■ Better retention of color, texture and taste in the sample dried at 40 °C	Wankhade et al., 2013

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