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Review

Drying and the Different Techniques

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Abstract: Drying is removing a large portion of the water contained in a product in order to considerably reduce the reactions which leads to deterioration of the products. In less developed countries where industry is not very important there is a general feeling that drying is an easy operation and not too much input is needed and anybody can do it. Drying of foods is a complex business and a mere translation from other fields is not often advisable. Drying plays an important role in food and agricultural industries and is the oldest method of preservation. The main feature of this process consists on lowering the water content in order to avoid or slow down food spoilage by microorganism. This review focuses upon conventional and new drying techniques and their advantages, limitations and applications.

Keywords: drying; moisture; preservation; food spoilage; deterioration of products

1. Introduction

Drying is probably the oldest and the most important method of food and vegetables preservation practiced by humans (Doymaz, 2005a). It removes moisture and preserve products. Drying process involves heat and mass transfer (Adeboye and Oputa, 1996; Bamire and Oke, 2003). Drying which is the removal of moisture prevents the growth and production of microorganisms that causes decay; it minimizes the moisture-mediated deteriorative reactions. It also can cause substantial reduction in weight and volume, minimizing packaging, storage and transportation costs and enables storability of the product under ambient temperature (Owolarefe *et al*., 2007). During drying a lot of changes occur which can be structural and physico-chemical modifications that can affect the final product quality (Doymaz, 2005; Okos *et. al*, 1992).

Thermal damage incurred by a product during drying is directly proportional to the temperature and time involved (Lin et al.1998), which means that decreasing drying time can improve the quality of products.

However, drying has always been of great importance for the preservation of food, thus, the major reason of drying food products is for the reduction of moisture content. Improvement of product quality and reduction of post-harvest losses can only be achieved by the introduction of suitable drying technologies (Bala and Janjai, 2009).

Drying processes can be classified into four categories namely solar drying, atmospheric drying, sub atmospheric drying and novel drying technologies (Jayaraman and Gupta, 1995). Solar drying includes sun or natural dryers, solar dryers-direct, solar dryers indirect and hybrid or mixed systems. Atmospheric drying is either continuous or batch. Continuous drying utilizes dryers such as spray dryer, fluidized bed dryer, belt dryer, rotary dryer, tunnel dryer and drum dryer whereas batch drying requires dryers such as kiln dryer, cabinet or compartmental dryer and tower dryer. Sub-atmospheric drying includes vacuum shelf dryer, continuous vacuum dryer and freeze dryer. Novel drying technologies are microwave drying, infra-red radiation drying, electric or magnetic field drying, superheated steam drying, explosion puffing, foam mat drying, acoustic drying and osmotic dehydration (Jayaraman and Gupta, 1995).

In this paper, drying methods will be studies and their principles of operation, uses and the advantages and disadvantages of these methods in terms of their drying effectiveness and efficiency will be addressed, with the future prospects of drying and dryers discussed.

2. Methods of Drying

The essence of drying in the industries, especially processing and food industry cannot be overestimated. To achieve the expected drying of materials, several methods of drying have been developed and further researches are still been carried out. Some of these include but not restricted to the following listed.

2.1. Air Drying

Air-drying is considered to be one of the simplest and most economical ways of commercially processing fruit and vegetables (Brennan *et al*, 1990). This process takes place when materials are dried with unheated forced air, taking advantage of its natural drying potential. The process is slow and weather dependent (Roy, 2015).

Air-drying could be considered as appropriate to developing countries as the product, suitably packaged, can be stored for several months without the risk of spoilage (Marriott and Lancester, 1983).

2.2. Hot- air Drying

In hot-air drying, enough water must be removed to lower the water activity to a level which inhibits the growth of microorganisms and reduces the rate at which enzymatic and non-enzymatic reactions occur. Thus, one of the primary requirements in using hot-air drying is to understand the drying process, to be able to predict drying times, establish the distribution of moisture throughout the solid pieces during drying and the influence of the processing variables such as air temperature and velocity, pretreatment and the size of the pieces on drying behaviour (Johnson**,** et al, 1998). Hot-air drying is an alternative drying method. Using hot air dryers leads to a more uniform, hygienic and attractive products that can be produced rapidly (Karathanos and Belessiotis, 1999).

2.3. Sun Drying

Sun drying is one of the oldest and accessible processes used by farmers to preserve different foodstuffs. It is an efficient way to reduce wastes (Touré, 2012). Sun drying is the traditional method of drying in developing countries and it denotes the spreading of foodstuff in the sun (direct sunlight) on a suitable surface such as mat, roof, or drying floors (Bindu et al, 2016).

Sun-drying method is cheaply executed, takes a longer time and may be prone to contaminations from microorganisms due to unhygienic exposures (Yarkwa and Uvir, 2015). Moreover, the direct exposure to sunlight, or more precisely ultra-violet radiation, can greatly reduce the level of nutrients such as vitamins in the dried product (Tunde and Akitunde, 2011).

Folaranmi (2008) asserted that sun drying is plagued with in – built problems, since the product during drying is unprotected from theft, rain, storm, windborne dirt, dust and infestation by insects, rodents, and other animals, encourages mould growth and may result in relatively high final moisture content. Consequently, the quality of dried products may be adversely affected, falling to meet the required local and international standards (Ivanova and Andonov, 2001; Abdelhaq and Labuza, 1987).

Moreover, since sun drying depends on uncontrolled factors, production of uniform and standard products is not expected. The quality of sun dried foods can be improved by reducing the size of pieces to achieve faster drying and by drying on raised platforms, covered with cloth or netting to protect against insects and animals (Bolea *et al*, 2012; Papu *et al*, 2014).

2.4. Solar Drying

Solar drying technology seems to be one of the most promising alternatives to reduce the post-harvest losses (Wiriya *et al*, 2009). Solar drying technology is one of the renewable energy resources particularly for low temperature heating and is a very attractive option for the small scale and resource poor enterprise (Chavda and Kumar, 2009). The solar dried products have much better colour and texture as compared to open sun dried products (Mulokozi and Svanberg, 2003). The attractiveness of solar dryers is further enhanced by its ability to dry the product rapidly, uniformly and hygienically to meet national and international standards with zero energy costs (Condori *et al*, 2001). The food is dried using solar thermal energy in a cleaner and healthier way (TaTEDO, 2007). However, it has been noted that, drying at higher temperatures may cause damage to the flavour, colour and nutrients of the dehydrated products (Praveenkumar *et al*, 2006). Due to the current trends towards higher cost of fossil fuels and uncertainty regarding future cost and availability, use of solar energy in food processing will probably increase and become more economically feasible in the near future.

They can be constructed from locally available materials at a relatively low capital cost and there are no fuel costs. Thus, they can be useful in areas where fuel or electricity are expensive, land for sun drying is in short supply or expensive, sunshine is plentiful but the air humidity is high

(Velayudham *et al*, 2015; Bindu *et al*, 2016). They give faster drying rates by heating the air to 10 - 30^{0}C above ambient, which causes the air to move faster through the dryer, reduces its humidity and deters insects. The faster drying reduces the risk of spoilage, improves quality of the product and gives a higher throughput, so reducing the drying area that is needed. However, care is needed when drying fruits to prevent too rapid drying, which will prevent complete drying and would result in case hardening and subsequent mould growth (Papu *et al*, 2014; Gavhale *et al*, 2015). Solar dryers also protect foods from dust, insects, birds and animals (Sacilik, *et al*, 2006). They allow for less spoilage and less microbiological infestation, thus leads to improved and more consistent product quality (Tunde and Akitunde, 2011).

Solar drying technology produces better quality products and is considered to be an alternative for drying agricultural products in developing countries (Gürlek, *et al*, 2009). However, dependency on weather for drying operation is one of the setbacks in solar drying technology. (Prakash and Kumar, 2013; Sontakke and Salve, 2016).

2.4.1. Mechanism of solar dryer

A solar dryer has three main components and these are drying chamber, solar collector and some type of airflow system. A drying chamber is an enclosed, insulated structure inside which both solar collection and drying takes place. It is often insulated to increase efficiency (Chavda and Kumar, 2009). The solar collector (or absorber) is often a dark coloured box with a transparent cover and Glass is recommended for the absorber cover. The solar collector can be of any size and should be tilted toward the sun to optimize collection. The size of solar collector required for a certain size of dryer depends on the ambient temperature, amount of sun, and humidity (Green and Shwartz, 2001; Chavda and kumar, 2009)

Tilting the collectors is more effective than placing them horizontally, for two reasons. First, more solar energy can be collected when the collector surface is more nearly perpendicular to the sun's rays. Second, by tilting the collectors, the warmer, less dense air rises naturally into the drying chamber (Chua and Chou, 2003; Prakash and Kumar, 2013).

Solar dryers use one of two types of airflow systems which are natural (passive) and forced (active) convection. The natural convection utilizes the principle that hot air rises, and forced convection dryers force air through the drying chamber with fans. The effects of natural convection may be enhanced by the addition of a chimney in which exiting air is heated even more (Eltawil *et al*, 2012). Additionally, prevailing winds may be taken advantage of (Green and Shwartz, 2001; Zomorodian, *et al*, 2007).

The Solar Dryers may be classified into several categories, depending upon the mode of heating or the mode of their operations and airflow systems. Depending on how heat is provided for drying, solar dryers can be broadly divided into four categories namely; direct, indirect, mixed and hybrid types (Fudholi *et al.*, 2010; El-Sebaii and Shalaby, 2012).

2.5. Infra-red Drying

Infra-red is usually the best choice where a process requires high temperature and a lower capital expense. It is used for heat setting as well as drying and curing thinner coatings, such as paints, ink paper, textiles, adhesives in making films for appliances and electronics (Pawar and Pratape, 2017).

Infra-red drying involves heat transfer by radiation between a hot element and a material at lower temperature. The peak wavelength of the radiation is dependent on the temperature of the heated element. Thermal radiation is considered to be infrared in the electromagnetic spectrum between the end of the visible 0.78µm and 1000 µm (Sulistiyanti et al, 2009).

In this method heating the product is performed without undesirable changes in structure, so the structural quality of the product is improved, its biological yield is increased and costs of operation are decreased (Strumillo and Kudra, 1987). Another advantage of drying using infrared radiation is the minimization of product losses such as color change and shrinkage. Also IR radiation causes rapid and direct heat concentration on the material compared to the convective dryers in which part of the heat is absorbed by the inlet air and wasted. IR drying method in fact developed for high drying rate without the risk of burning the material (Nonhebel, 1973).

In infrared method of drying, effective diffusion coefficient of moisture showed an increasing trend with increasing radiation intensity and decreasing airflow rate. Increasing the intensity of radiation, elevated the temperature gradient of the surface and underlying layers of the product. Also, decreasing the air velocity by reducing the cooling effect of air flow in this method increased the diffusion coefficient inside the product (Saeid *et al*, 2011).

2.6. Microwave Drying

Microwave drying is an alternative method that has been used in the food industry. Microwaves are electromagnetic waves which range between 0.3 GHz and 300 GHz. The most commonly used frequencies are 915 MHz and 2450 MHz. The microwave heating method dehydrates food by interactions between the electromagnetic energy and polar molecules within the material. Polar molecules rotate in response to the applied oscillating electromagnetic waves. The reorientation of these molecules in a high frequency electric field occurs frequently and rapidly, resulting in molecular friction that generates heat (McGurk *et al*, 2017). Microwave heating is a desirable alternative drying method since it enhances the energy efficiency and has less negative impact on the quality of the dehydrated products (Huang, 2013).

Microwave drying of products has become common because microwave drying prevents a decline in the quality of the product and; ensures the rapid and efficient distribution of heat within the material (Li *et al.,* 2009; Dong *et al* 2011; Silva *et al*., 2007). Moreover, microwave drying reduces drying time and saves energy and also producing high quality dry products (Balbay *et al*., 2011; Li *et al*., 2010).

Applying microwave energy under vacuum combines advantages of both vacuum drying and microwave drying as far as improved energy efficiency and product quality are concerned. Vacuum dried materials are characterized by higher porosity, depending on level of vacuum and less deterioration of colour and volatile aroma (Larrosa *et al*, 2017; shiby *et al*, 2015).

2.7. Drum Drying

In a drying operation, liquid, slurry, or puree material is applied as a thin layer onto the outer surface of revolving drums that are internally heated by steam (Kasiri *et al*, 2004; Tang *et al*, 2010).

In drum drying, a large amount of thermal energy is released by the condensing steam in the drum and conducted through drum wall to the product. During drying, a product may go through three general periods. The first is the initial heating period where wet materials are applied onto the drum surface in a thin layer. Intensive heat transfer occurs due to a great temperature difference between the drum surface and the wet product and product temperature increases rapidly to reach the boiling point of free water. The second period is the constant product temperature period where after reaching the boiling temperature, a large amount of free water evaporates and product temperature remains constant. The drum surface temperature, however, decreases due to an intense evaporative cooling. The third is the rising product temperature period, where after removing most of the free water, the amount of moisture for evaporation is dramatically reduced. The heat transferred from the steam gradually exceeds the energy used for evaporation. As a result, drum surface temperature increases. The bound water starts to play a major role in controlling the rate of evaporation. As bound water has a higher boiling temperature, product temperature gradually increases as drying proceeds (Rodriguez, *et al,* 1996).

In the operation of a drum dryer, a delicate balance needs to be established among feed rate, steam pressure, roll speed, and thickness of the product film. It is desirable to maintain a uniform film on the drum surface to ensure maximized throughput and consistent final moisture content. Problems, however, are often encountered due to fluctuations in the moisture content and thickness of the feed. Means have been developed to automatically detect the moisture content and temperature, integrated with automated feedback control to minimize the fluctuations. (Rodriguez, *et al,* 1996)

Products containing high sugar contents, such as tomato puree, may be difficult to remove from the drums at high temperatures due to the thermo plasticity of those materials. A cooling mechanism (e.g., a jet of cold air) may be used at the location just before the product reaches the scraper. The purpose of the cooling is to bring the product from a rubbery state into a glassy state to facilitate separation of the product from the drum surface (Tang *et al,* 2010).

Drum dryers are used in the food industry for drying a variety of products, such as, milk products, baby foods, breakfast cereals, fruit and vegetable pulp, mashed potatoes, cooked starch, and spent yeast (Rodriguez *et al*, 1996).

2.8. Spray Drying

This technique enables the transformation of feed from a fluid state into dried particulate form by spraying the feed into a hot drying medium. It is a continuous particle processing drying operation. The feed can be a solution, suspension, dispersion or emulsion. The dried product can be in the form of powders, granules or agglomerates depending upon the physical and chemical properties of the feed, the dryer design and final powder properties desired (Michael, 1993).

Spray drying is presently one of the most exciting technologies for the pharmaceutical industry, being an ideal process where the end-product must comply with precise quality standards regarding particle size distribution, residual moisture content, bulk density and morphology. The production of particles from the process of spraying has gained much attention in recent years (Suthur *et al,* 2009).

2.9. Oven Drying

In conventional oven heating, the heat is transferred from the surface to the interior of the material. Thus a pressure is generated between the surface and interior due to evaporation, such that the interior moisture is driven out and evaporation continues at the surface. However, conventional oven heating has low energy efficiency with negative quality effects (Huang, 2013).

The oven takes two or three times longer to dry food when compared with other dryers. Thus, the oven is not as efficient and uses more energy. There are two types of ovens namely batch and conveyor ovens. The oven uses convective process (force air convective and gravity convective). It is used in various industrial applications for drying, curing (rubber), baking, etc. Lapses in oven drying are due to induced evaporation. Explosion can occur since the product when dried reaches its combustion level. It is difficult to get humidity of the oven due to lack of flow velocity for easy circulation (Brennand, 1994).

2.10. Vacuum Drying

Vacuum drying is a process that allows for materials to be dried in a reduced pressure environment, which lowers the heat needed for rapid drying. This drying method is recommended to counter the undesirable effects of Infrared drying method and to improve the product quality, as well as nutritional value. The method allows effective moisture elimination under low pressure (Jaya and Das, 2003). Vacuum drying enhances the mass transfer because of an increased vapour pressure gradient between the inside and outside of the product (Pere and Rodier, 2002).

Vacuum dryers offer low-temperature drying of thermolabile materials and are suitable for solvent recovery from solid products containing solvents (Parikh, 2015) and also less energy usage and hence greater energy efficiency, improved drying rates, and in some cases, less shrinkage of the product (Alibas, 2007; Alibas, 2009).

2.11. Freeze Drying

Lyophilization or freeze drying is a process in which water is frozen, followed by its removal from the sample, initially by sublimation (primary drying) and then by desorption (secondary drying). Freeze drying is a process of drying in which water is sublimed from the product after it is frozen.(Akers *et al*,1987; Chien and Yiew, 1981). The term “lyophilization” describes a process that produce a product that “loves the dry state” (Remington, 2000a).

Intact cake, sufficient strength, uniform color, sufficiently dry, sufficiently porous, sterile, free of pyrogens, free of particulates, chemically stable are the desired characteristics freeze dried products (Khairnar *et al*, 2013; Pandhare *et al*, 2015; Rajeevini *et al*, 2015).

Three methods of freeze drying are commonly used namely; manifold drying, batch drying, and bulk drying. Each method has a specific purpose, and the method used depends on the product and the final configuration desired. Since freeze drying is a change in state from the solid phase to the gaseous phase, material to be freeze dried must first be adequately prefrozen (Khairnar *et al*,2013; Gaidhani *et al*, 2015; Rajeevani *et al*, 2015).

It is a drying process applicable to manufacture of certain pharmaceuticals and biologicals that are thermo labile or otherwise unstable in aqueous solutions for prolonged storage periods, but that are stable in the dry state. The knowledge of how to control, or at least manipulate, the freezing step will help to develop more efficient lyophilization cycles and biopharmaceutical products with an improved stability (Kasper and Friess, 2011; Esfandiary *et al*, 2016).

2.12. Osmotic Drying

Osmotic dehydration is the phenomenon of removal of water from lower concentration of solute to higher concentration through semi permeable membrane results in the equilibrium condition in both sides of membrane (Tiwari 2005). Osmotic dehydration found wide application in the preservation of food-materials since it lowers the water activity of fruits and vegetables. Osmotic dehydration is preferred over other methods due to their color, aroma, nutritional constituents and flavor compound retention value (Yadav and Singh, 2014; Alakali *et al.,* 2006; Torres *et al.,* 2006; Pokharkar and Prasad, 1998). Osmotic dehydration results in increased shelf-life, little bit loss of aroma in dried and semidried food stuffs, lessening the load of freezing and to freeze the food without causing unnecessary changes in texture (Petrotos and Lazarides, 2001).

Osmotic dehydration involves the immersion of foods (fish, vegetables, fruits and meat) in osmotic solution such as salts, alcohols, starch solutions and concentrated sugars, which some extent to dehydrates the food (Erle and Schubert, 2001). Different types of solutes such as fructose, corn syrup, glucose, sodium chloride and sucrose are used as osmotic agent for OD (Azuara and Beristain, 2002).

It involves dehydration of fruit slices in two stages, removal of water using as an osmotic agent (osmotic concentration) and subsequent dehydration in a dryer where moisture content is further reduced to make the product shelf stable (Ponting, 1973).

Therefore, the characteristics of the product can be varied by controlling temperature, sugar syrup concentration, concentration of osmosis solution, time of osmosis etc., to make osmotic concentration process faster (Chavan and Amarowicz, 2012).

2.13. Foam Mat Drying

The foam mat drying is a process in which the trans-formation of products from liquid to stable foam is followed by air drying (Franco *et al*, 2015; Sangamithra *et al*, 2015; Affandi *et al*, 2017).

Stable gas-liquid foam is the primary condition for successful foam drying. Proteins, gums and various emulsifiers such as glycerol monostearate, propyleneglycerol monostearate, carboxymethyl cellulose [CMC], trichlorophosphate are used as foaming agents. Mixtures are whipped to form stable foams using blender or specially designed device. The foam is then spread as a thin sheet or mat and exposed to a stream of hot air until it is dried to desired moisture content (Rajkumar *et al*, 2007). Drying is carried out at relatively low temperatures to form a thin porous honeycomb sheet or mat, which is disintegrated to yield a free-flowing powder. The larger surface area exposed to the drying air is the main cause of moisture removal acceleration (Brygidyr *et al*. 1977). However, capillary diffusion is also the main reason for the moisture movement within the product during foam mat drying (Sankat and Castaigne 2004).The dried product obtained from foam mat drying is of better quality, porous and can be easily reconstituted.

This process can be used for large-scale production of fruit powders because of its suitability for all types of juices, rapid drying at lower temperature, retention of nutritional quality, easy reconstitution and is cost-effective for producing easily re-constitutable juice powders. Fruit juice powders obtained through this process have high economic potentials over their liquid counterparts such as reduced volume or weight, reduced storage space, simpler handling and transportation, and much longer shelf life (Sangamithra *et al*, 2015; Sharifi *et al*, 2015; Chandrasekar *et al,* 2015; Singh and Dixit, 2014;). The fruit powders obtained through this method can find applications in snacks, beverages, ice creams, bakery products, as a starter for the preparation of instant foods, pastes, etc. (Sangamithra *et al*, 2015)

A proper understanding of selection of suitable foaming agents, foaming properties such as foam density, foam expansion, foam stability, method of drying, drying temperature, are required for the process optimization, in order to obtain products with better nutritional characteristics and process yield (Kandasamy *et al*, 2014; Kumar *et al*, 2015; Ismaila *et al*, 2016).

2.14. Impingement Drying

Air impingement drying is not a new technology but it is a complicated process and it is used for food and agricultural product processing. Impingement drying can be affected by many factors such as drying temperature, air velocity and relative humidity which can influence its drying characteristics and quality (Xiao *et al*, 2010).It is an efficient drying process and has been used successfully in paper and textile industries and also with the purpose of drying, cooling, or heating different artefacts and metals. It has only recently been applied to food products (Moreira 2001). One of the obvious advantages of impingement drying techniques is rapid drying. In air impingement processing, the air impinges on the product surface at high velocity, removes thermal boundary layers of moisture and cold air and increases the rate of heat transfer (Anderson and Singh 2006). The high-velocity air from the nozzles creates a bed of hot air that suspends the products; thus, temperature at the center of the product rises rapidly to the drying air temperature. So, air impingement drying can greatly accelerate heat transfer and reduce process time (Mujumdar 1986). Uniform, hygienic and attractively colored product can be produced rapidly using air impingement drying (Xiao *et al*, 2010).

Energy consumption and environmental issues are naturally important factors in drying processes and impingement jet drying are no exception (Ljung et al, 2017).

2.15. Acoustic Drying

This process can cause the removal of moisture from a material under high intensity sound field (audible and ultrasound frequency range). There are two phenomenas involve in acoustic drying. In primary phenomena, the factors involve in acoustic drying are sound frequency, intensity, sound pressure and particle velocity while the change of hydrodynamic condition, barometric pressure and turbulent agitation of air at the boundary layer close to the material is the secondary phenomena(Seya and Otsuka, 1980; Kouchakzadeh, 2013).

2.16. Explosion Puffing Drying

This is a new drying technology that uses high temperature and pressure to dry products. It has the combine advantages of a convective hot air and a vacuum freeze drying. The puffed fruits and vegetables are natural, healthy foods and contain plentiful nutrition, also it has excellent qualities and wide application prospects (Sullivan and Craig Jr, 1994; Kozempel *et al*, 2008).

2.17. Hybrid Dryers

There are different types of hybrid dryers available with different operational techniques and designs. Their major advantages are increased drying rates, better, safer, efficient and effective and good quality of products. Solar dryers may be useful as hybrid dryer when added as a means of heating air for artificial dryers to reduce fuel costs (Fellows, 1997). The combined process of osmotic dehydration (OD) and freezing is called osmodehydrofreezing which is used to get better texture properties of fruits and vegetables as well as lessen the structural collapse and drip loss. Giannakourou and Taoukis (2003) studied that change in quality of osmodehydrofrozen of green peas treated with maltitol and trehalose combined with $CaCl_2$ and NaCl and they observed that osmotic treatment lowered the quality changes in term of texture, color and retention of ascorbic acid for frozen samples. The dehydrofreezing process also concerned with improving of quality (Khan, 2012).

Infrared radiation has been used in conjunction with several drying methods because it has advantages of increasing the drying efficiency (Ratti and Mujumdar, 1995). Examples are the Infrared – vacuum drying (Swasdiasevi *et al*, 2009; Saetan *et al*, 2013; Yunhong *et al*, 2015; Alaei and Chayjan, 2015), Foam mat – cabinet dryer (Thirupathi *et al*, 2008; Rajkumar *et al*, 2007), microwave – vacuum dryer (Berteli *et al*, 2009); Yongsawatdigul and Gunasekaran,1996); Clary *et al*, 2007), vacuum – spray dryer (Wisniewski, 2015), oven vacuum dryer (Amellai and Benamara ,2008); Kumaravel *et al*, 2012), low – pressure superheated steam drying and far infrared radiation (LPSSD – FIR),Nimmol *et al*, 2007;

Pawar and Pratape (2017), impingement and superheated steam drying (Moreira, 2001), impingement and hot air drying (Xiao *et al*, 2012; Jambunathan *et al*, 1992; Xiao *et al*, 2014), etc. Efforts are been made to design more of these hybrid dryers which can perform better under adverse weather conditions.

3. Advantages, Limitations and Applications of Drying Methods

Table 1 gives a summary of all the drying techniques discussed with their advantages, limitation(s) and application(s).

Table 1: Advantages, limitations and applications of drying methods

S/N	METHOD	ADVANTAGE(S)	LIMITATION(S)	APPLICATION	REFERENCES
1.	Natural(Open) air Drying	• Simplest and most economical way of drying. • Use unheated heat(free air) • Natural drying potential • Can be stored for some months without spoilage • No equipment • Kept in open space	• Has problem of contamination, infestation, microbial attack and the drying time is long. • Cannot handle large quantities and to achieve consistent quality standards. • Problem of predators • Process is slow and weather dependent.	Fruits and Agricultural products e.g corn, rice, millet, bean, pepper, okro, groundnut, yam, sorghum, plantain chips, etc Practiced in tropical countries.	Itodo et al, 2002 Togrul and Pehlivan, 2004 Bolaji, 2005
2.	Hot air Drying	• Rate of drying is fast • Low capital and maintenance cost • Flexible in operation • Water activity will be reduced to a level that inhibits growth of microorganism • Influence the processing variables e.g temperature, air velocity, humidity	• Low energy efficiency • Quality loss and long drying time during falling rate period • Relatively poor quality/control as food dries rapidly if close to heat source.	Food and agricultural products	Boudrioua et al, 2003 Johnson et al , 1998
3.	Fluidized Bed drying	• Thorough mixing of solids which results in efficient mass and heat transfer. • Rapid and economic drying • Ease of control	• Loss of product qualities such as color, texture,flavour and nutrients	Food and Agricultural products	Sagar and Kumar, 2010 Elkhodiry et al, 2015

		• Temperature uniformity • Easy handling and transport of material			
4.	Sun Drying	• Natural heat from sun • Cheap to use and economical • Spreading of foodstuff under direct sunlight on a suitable surface • Require little expertise • Efficient(drying) way to reduce waste • Reducing the thickness of the product for faster drying.	• Poor quality due to vulnerability to contamination by insects, birds and dust • Direct exposure to sunlight (or ultra – violet radiation) can reduce the level of nutrients. • Unprotected from theft, rain and infestation • May result in relatively high final moisture content which encourages mould growth • Takes longer time to dry • Due to uncontrollable factors, production of uniform and standard products is not expected.	Food and agricultural products	Ivanova and Andonov, 2001 Yarkwa and Uvir, 2015 Abdelhaq and Labuza, 1987 Karathanos and Belessiotis, 1997 Bolea et al, 2012 Papu et al, 2014
5.	Solar Drying	• Require little maintenance • Low temperature heating • Most cost effective: uses energy from the sun to heat a stream of air to provide air. • Uses natural or forced convective air • Less contamination because it is in a closet • Less susceptible to adverse weather conditions • Depending on the size and sophistication of the dryer. • Reduces land required when compare to air drying.	• Requires adequate solar radiation • UV radiation can damage food nutrients • Expensive than direct sun drying • Need skilful fellow to construct. • Each location have different configuration/type	Food and agricultural products	Akbulut and Durmus, 2010 Bolaji and olalusi, 2008 Chavda and Kumar, 2009 Wiriyi et al, 2009 Mulokozi and Svanberg, 2003 Praveenkumar et al, 2006 Fellows, 1997 Gurlek et al, 2009 Sontakkre and Salve, 2016 Condori et al, 2001

		• Attractive to small scale entrepreneur • It is hygiene, prevent contamination and infestation			
6.	Infra-red Drying	• Requires heating at high temperature • Cost of operation is reduced minimization of product losses • Rapid and direct heat concentration on the material. • Gives high drying rate without burning the material.	• Has an increasing radiation intensity • Decreases airflow rate • Diffusion coefficient inside the product is increased. • Requires electricity • Dryer is a sophisticated one and maybe difficult to repair.	It is used for heat setting as well as drying and curing thinner coatings such as paints, ink paper, textiles, adhesives in making films for appliances and electronics.	Sulistiyanti et al, 2009 Pawar and Pratape, 2017 Ratti and Mujumdar, 1995 Nonhebel, 1973 Saeid et al, 2011
7.	Microwave Drying	• Short or reduces drying time • Temperature and moisture gradients are in the same direction • Enhances energy efficiency and has distribute more thermal efficiency • Improve quality and flavour of the product.	• Non uniform heating (uneven distribution of microwave field can occur) • Overheating may take place • Quality deterioration can take place.	Food, agricultural and dairy products	Huang, 2013 Balbay et al, 2011 Li et al, 2010 Larrosa et al, 2017 Shiby et al, 2015 Silva et al, 2007 Dong et al, 2011
8.	Drum Drying	• Have high drying rate • High energy efficiencies • Suitable for slurries drying	• High capital cost of machined drum • High damage to sensitive foods • Electricity failure could affect the operation • Fluctuations in the moisture content and thickness of the feed • Product like puree may be difficult to remove at high temperature due to the thermal plasticity.	Food industry e.g Potato flakes, cereals, fruits purees, baby foods, etc	Rodriguez et al, 1996 Kasiri et al, 2004 Tang et al, 2010

9.	Spray Drying	• Rapid drying • Low labour cost • Relatively simple operation and maintenance • Reduces the transport weight of foods • Compliance with the product standards.	• High capital cost • High feed moisture content to ensure that it is pump to the atomiser	Food processing and Pharmaceutical industries. Products like milk, ice cream , egg yoghurt, juice, etc	Michal, 1993 Surthur et al, 2009
10.	Oven Drying	• Removes moisture content • Low labour cost • Flexibility in operation • Less contamination from infestation • Cost efficient	• Longer drying time • Harder to control than drying with dehydrator • Not efficient and uses more energy • Explosion might occur due to induced evaporation • Case Harding of product may take place because of much heat	Food and agricultural products	Bennand, 1994 Huang, 2013
11.	Vacuum Drying	• It allows effective moisture elimination under low pressure • Enhances the mass transfer because of an increased vapour pressure gradient between the inside and outside of the product • Improved drying rates • Offer low-temperature drying for thermolabile materials • Suitable for solvent recovery from solid products containing solvents	• Operating under low pressure only • Uses to counter infra red effect • Uses much energy • Less shrinkage of the product	Food and agricultural products	Parikh, 2015 Alibas,2007,2009 Alaei and Chayjan, 2015 Jaya and Das, 2003 Pere and Rodier, 2002
12.	Freeze Drying	• Uses sublimation technique • Oxidizable substances are well protected under vacuum conditions	• Volatile compounds may be removed by high vacuum • Single most expensive unit operation	• Pharmaceuticals and biologicals that are thermolabile • Pharmaceutical and	Long *et al*, 2013 Rajeevini *et al*, 2015 Harish *et al*, 2017) Gatin *et al*, 2008 Khairnar *et al*, 2013

		• Long preservation period owing water removal • Loading quantity accurate and content uniform • Little contamination owing to aseptic process • Minimal loss in volatile chemicals and heat-sensitive nutrient and fragrant components • Minimal changes in the properties because microbe growth and enzyme effect can not be exerted under low temperature • Transportation and storage under normal temperature • Rapid reconstitution time • Constituents of the dried material remain homogenously dispersed • Product is process in the liquid form • Sterility of product can be achieved and maintained	• Stability problems associated with individual drugs • Some issues associated with sterilization and sterility assurance of the dryer chamber and aseptic loading of vials into the chamber.	biotechnology industry • In Food Industry • In Technological Industry for chemical synthesis and bioseparations	Pandhare *et al*, 2015 Akers *et al*,1987 Chien and Yiew, 1981 Sunderland, 1980 Shuka, 2011; Ciurzynska and Lenart,2011 Gaidhani *et al*, 2015 Sanjith and Gatin, 1993
13.	Osmotic Drying	• Removal of water from lower concentration of solute to higher concentration through semi permeable membrane results in the equilibrium • It lowers the water activity • Retention value of color, aroma, nutritional constituents and flavor compound	• Some of the osmotic agent may be costly and not readily available. • The high viscosity of the osmotic solution • low density difference between the solid and the solution • It is a time taking process • The reduction in acidity level reduces the	Preservation of food-materials Fruits and vegetables such as banana, sapota, pineapple, mango, and leafy vegetables, etc	Tiwari, 2005 Yadav and Singh, 2014 Alakali *et al.*, 2006; Torres *et al.*, 2006 Petrotos and Lazarides, 2001 Azuara and Beristain, 2002 Giannakourou and Taoukis, 2003

		• Decrease the energy costs • Lessening the load of freezing • Inhibiting the browning of enzymes • Conducted at low or ambient temperature.	characteristic taste of some products		Khan, 2012 Pokharkar and Prasad, 1998 Ponting, 1973 Chavan and Amarowicz, 2012
14.	Foam mat Drying	• Used for large-scale production of fruit powders because of its suitability for all types of juices • Rapid drying at lower temperature • Retention of nutritional quality • Easy reconstitution of the product powders • cost-effective for producing easily re-constitutable juice • have high economic potentials over their liquid counterparts • much longer shelf life	• Low bulk density • High cost of water removal • Energy demand Reduces drying time • Necessity to addition of forming agent for stability of the liquid or semi – solid food material which make such products unavailable in their pure form.	In food processing industry: Applications in snacks, beverages, ice creams, bakery products, as a starter for the preparation of instant foods, pastes, etc	Sangamithra *et al*, 2015 Chandrasekar *et al*, 2015 Franco *et al*, 2015 Affandi *et al*, 2017 Rajkumar *et al*, 2007 Brygidyr *et al*. 1977 Sankat and Castaigne 2004 Kudra and Ratti 2006 Kandasamy *et al*, 2014 Kumar *et al*, 2015 Ismaila *et al*, 2016 Kadam *et al*. 2010a
15.	Impingement Drying	• Most suitable for products that have a high surface area • Used to increase the convection(i.e convective heat transfer) • Rapid drying • increases the rate of heat transfer	• Thermal damage incurred by a product during drying is directly proportional to the temperature and time involved • Heat transfer at the surface of the product • High capital cost • Web tension issues • Energy consumption and environmental issues	Paper, textile and metal industry. Food and agricultural product processing.	Ljung et al, 2017 Xiao *et al*, 2010 Mujumdar 1986 Anderson and Singh 2006 Moreira, 2001 Lin et al.1998
16.	Acoustic Drying	• Effective at lower temperatures • Uses high intensity	• It is expensive • Usefulness is limited because of sophistication • Needs to be used in combination with	Pharmaceuticals, food and chemical industry	Seya and Otsuka, 1980 Kouchakzadeh, 2013

		• It improve elasticity • The rate of water removal increased when acoustical energy is applied • Enhancing drying	other process(e.g heating) • Posible damage by free radical • Complex mode of action		
17.	Explosion Puff Drying	• Faster rehydration of product • Rapid drying • Gives low moisture content • Retention of texture and flavour of product • Lower nit processing cost • Processing of large pieces of product feasible	• Labour intensive • Loss of product intergrity • High level of heat	Food and agricultural products like apple, blueberries, carrots, potatoes, etc	Sullivan and Craig Jr, 1984 Kozempel et al, 2008

4. Future Prospects

Drying researches and developments have seen exponential growth over the past three decades. Initially driven by the need to conserve energy in this highly energy-intensive operations found in almost all industrial sectors, and focuses on product quality, environmental impact, safety issues, new products, and processes. Drying provides challenging areas for multi- and cross-disciplinary research of fundamental as well as applied nature coupling transport phenomena with material science. New areas of development in drying technologies are Hybrid drying, Superheated Steam drying, Pulse Combustion drying, Intermittent drying, Spray drying, Impingement drying, etc. Further development in design of dryers like the continuous foam dryer for example will help to achieve stable foam, which in turn results in dried powder of high quality and also studies on the microstructure characterization of foams and foam-dried powders, computer simulation techniques for the prediction of moisture and temperature distribution in the product requires the attention of researchers for further up gradation of the process. It is highly expected that the further improvement in foam mat drying process, as well as the use of other drying method combined with foam mat drying, will intensify the adoption of this renewed method in the food industry (Sangamithra *et al*, 2015).The need for industry-academia interaction and for a stake of industry in academic research is noted as a key step towards successful transfer of innovative drying technologies to industry (Mujumdar, 2004).

5. Conclusion

Drying is an important process to preserve raw food materials and the drying process occurs when water vapor is removed from its surface into the surrounding space, resulting in a dried material with an extended shelf life and reduced water activity of food products. During drying, the moisture content can be reduced to a level ranging 1 – 5%, which avoids microbial and undesirable enzymatic reactions.

There is lots of drying methods and each of these has its own advantages and disadvantages and could be applied effectively. We also have a combination of two or three methods as in the cases of hybrid which can give better drying.

Traditional drying methods (sun, oven and solar) are simple to use, however they are not economical. They have low energy efficiency and require longer drying time. As a result, it negatively affects the flavour, nutrient content, and may lead to undesirable colours in the dried end product. In addition, case-hardening is another problem in drying products with these traditional methods. Since the evaporation of surface water is faster than the movement of water inside the food, case hardening occurs which prevents the proper drying of the food to its optimal moisture level for storage. The formation of the outer hard case not only affects the appearance but also the taste of the dried products. Compared to conventional drying methods, microwave drying has more thermal efficiency and provides an end product with improved quality and flavour (Huang, 2013).

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