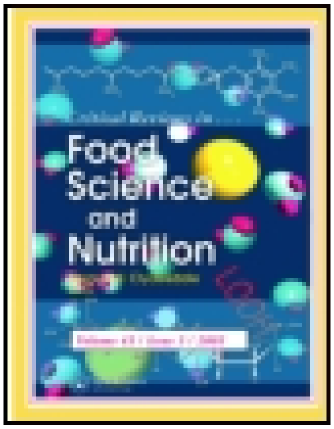

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Quality Properties of Fruits as Affected by Drying Operation

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Abstract

The increasing consumption of dried fruits requires further attention on the quality parameters. Drying has become necessary because most fruits are highly perishable owing to their high moisture content and the need to make them available all year round and at locations where they are not produced. In addition to preservation, the reduced weight and bulk of dehydrated products decreases packaging, handling and transportation costs. Quality changes associated to drying of fruit products include physical, sensory, nutritional, and microbiological. Drying gives rise to low or moderate glycemic index (GI) products with high calorie, vitamin and mineral contents. This review examines the nutritional benefits of dried fruits, protective compounds present in dried fruits, GI, overview of some fruit drying methods and effects of drying operations on the quality properties such as shrinkage, porosity, texture, color, rehydration, effective moisture diffusivity, nutritional, sensory, microbiological and shelf stability of fruits.

Keywords: Thermal processing, shrinkage, porosity, rehydration, nutrients, sensory properties, pretreatment, dried fruits.

Introduction

Recent reviews on fruits have been on functional properties and postharvest utilization of commercial and non-commercial banana cultivars (Anyasi *et al.* 2013), drying of exotic tropical fruits (Fernandes *et al*. 2010), advances in drying and dehydration of fruits and vegetables (Sagar and Suresh, 2010), and postharvest handling of avocado fruit (Kasim *et al*. 2013). Drying refers to the removal of moisture from a material with the primary aim of reducing microbial activity, product deterioration (Fellows, 2007; Jangam *et al*. 2010) and extension of shelf life. Figure 1 shows some dried fruits. Most food commodities contain enough moisture to permit the activity of native enzymes and micro organisms and drying is necessary to reduce their water activity and prevent microbial spoilage (Sivasanker, 2008; Ahmed *et al*. 2013). In addition to preservation, the reduced weight and bulk of dehydrated products decreases packaging, handling and transportation costs (Araya-Farias and Ratti, 2009). Most agricultural products are dried for improved milling or mixing characteristics in further processing (Ratti, 2008). However, each food product needs to be dried in a different way, using appropriate pre and post-processing step(s) such as osmotic dehydration, blanching, salting, and soaking together with proper dryer type so as to add satisfactory value upon drying (Mujumdar 2008; Chen and Mujumdar, 2008). The pre-processing steps are very important to reduce the drying load/time and to make better quality products. Some physical changes that may occur in fruit drying operation include shrinkage, puffing, crystallization and glass transitions. In some cases, desirable or undesirable chemical or biochemical reactions may occur leading to changes in color, texture, odor or other properties of the solid product (Ong and Law, 2010). These changes are very important in thermal processing of fruits. Therefore, this paper reviews the effects of drying operations on the quality parameters highlighting the texture, color, flavor, shrinkage, porosity, rehydration and effective moisture diffusivity, nutrients, and shelf stability of dried fruits.

NUTRACEUTICALS IN DRIED FRUITS

Nutraceuticals is defined as dietary supplements that deliver a concentrated form of a presumed bioactive food agent that is presented in a nonfood matrix and used with the sole aim of promoting health in dosages that exceed those obtained from normal foods (Zeisel 1999; Anyasi *et al*. 2013).Dried fruits are not only important sources of vitamins, minerals and fiber but also provide a wide array of bioactive components or phytochemicals. These compounds are not designated as traditional nutrients since they are not essential to sustain life, but play a role in health and longevity and have been linked to a reduction in the risk of major chronic diseases. Convincing evidence suggest that the benefits of phytochemicals may be greater than currently understood, since they affect metabolic pathways and cellular reactions believed to be involved in the etiology of a wide range of chronic diseases. Dried fruits are an excellent source of polyphenols (USDA, 2011). Table 1 is a list of important phytochemicals in fruits. Different dried fruits have unique phenolic profiles. For example, the most abundant in raisins are the flavonols, quercetin, kaempferol and phenolic acids i.e. caftaric and coutaric acids (Willamson and Carughi, 2010). Dates contain quercetin, apigenin and luteolin; dried plums are very high in chlorogenic and neochlorogenic acids; cranberries and blueberries are high in anthocyanins and anthocyanidins (Donovan *et al*. 1998). By virtue of their high polyphenol content, dried fruits are an important source of antioxidants in the diet (Wu *et al*. 2004; Vinson *et al*. 2005) contributing to the lowering of oxidative stress and so prevent oxidative damage to critical cellular components. Dried apricots and peaches are also important sources of carotenoids which are precursors of vitamin A and have antioxidant activity. Dried plums provide pectin, a soluble fiber that may lower blood cholesterol levels (Tinker *et al*. 1991), while raisins are a source of prebiotic compounds containing fructo oligosacharides like inulin, naturally occurring fiber-like carbohydrates that contribute to colon health (Carughi 2009). Dried fruits also contain organic acids such as tartaric acid in raisins and sorbitol in plums. These organic acids and fiber appear to work synergistically to maintain a healthy digestive system. They may also help increase the bioavailability of minerals such as calcium and iron (Spiller *et al*., 2003) in the diet.

GLYCEMIC INDEX OF DRIED FRUITS

All studies assessing the glycemic Index (GI) of traditional dried fruit show that they are low to moderate GI foods and that the insulin response is proportional to their GI. The GI of some fruits is as shown on Table 2. Carbohydrate containing foods are classified as high (GI above 70), moderate (56ï 69) or low (0ï 55) (GI Database, 2011). Foods with high fiber content generally have a low GI. However, other factors also contribute to a food's glycemic response, such as the type of carbohydrate or sugar present, the physical characteristic of the food matrix and the presence of organic acids. Factors thought to contribute to the glycemic response of dried fruits include the viscous texture when chewed; their whole food matrix; the presence of phenolic compounds and organic acids and the type of sugar present. About 50% fructose is present in most traditional dried fruit (Kim, 2008)·.

OVERVIEW OF SOME FRUIT DRYING OPERATIONS

Various researchers have discussed drying of fruits under different drying methods including microwave drying (Sousa and Marsaioli, 2004; Ganesapillai *et al*. 2011; Maskan, 2000; Drouzas and Schuber, 1996), oven (Ganesapillai *et al*. 2011; Yan *et al*. 2008; Leite, 2007; Singh *et al*. 2008; Boudhrioua *et al*. 2002), cabinet tray (Kowaliwale *et al*. 2007; Thuwapanichayanan *et al*. 2012), solar (Lahsasni *et al*. 2004; Togrul and Pehlivan, 2004) and freeze drying (Ezhilarasi *et al.* 2013; Ceballos *et al*. 2012). Table 3 shows drying methods for fruits.

Conventional hot air drying of fruits involves the use of dryers like continuous belt, tunnel, kiln and cabinet. Details about these dryers have been extensively discussed by Somogyi and Luh, 1986; Salunkhe *et al*. 1991 and Reynolds 1993. Dabhake and Khedkar (1980) observed that drying of raw mango pieces in a cabinet drier is much faster compared to sun drying. Mehta and Tomar (1980) reported that air circulation drier yield good quality guava and papaya slices. Kalra and Bhardwaj (1981) conducted an experiment using solar dehydration for fruit and vegetable products and concluded that dehydration model-II with high temperature 70-75 ^{o}C is more efficient as compared to dehydration model-I with low temperature 50-55^{o}C. Bhutani and Sharma (1988) found that drying of apricot processed at a faster rate in across flow dehydrator than in open sun drying. Thuwapanichayanan *et al* (2012) reported a drying time of 100,120 and 150 mins for drying banana foams added with different foaming agents: egg albumin, soy protein isolate and whey protein concentrate using a cabinet tray dryer. Using laboratory dryer at 60^{o}C with an air velocity of 1.1 m/s and various pre-treatments applied to examine the thin-layer

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drying behavior of black grapes, Doymaz (2006) observed the shortest drying time of 25 h when grapes were dipped in ethyloleate plus potassium carbonate solution. In the study of Pahlavanzadeh *et al*. (2001) on the drying of Iranian seedless white grapes (*sultana*) in a batch operation in a laboratory dryer, dipping grapes in an alkaline solution increased the drying rate substantially. Grapes dried in 450ï 900 min depending on pre-treatment and air temperature. The shortest drying time and best quality dried product were obtained with grapes dipped in 5% K_2CO_3 solution at 42^{o}C.

Microwave drying (MD) of fruits came into existence as a result of the desire to eliminate the inherent problems associated with conventional and solar drying methods. The problems connected to conventional is the lengthy drying time during the last stage of drying which may lead to serious injuries that could worsen the taste, color and nutritional content of the dried fruit while in the case of solar, the major problem is its inability to handle large quantities of fruit and achieve consistency in quality standards (Ratti and Mujumdar, 2005). The three main merits of MD include (i) high penetrating quality that leads to uniform drying of fruit products, (ii) selective adsorption by liquid water which leads to a uniform moisture profile within the fruit product and (iii) ease of control due to the rapid response of microwave heating. Ganesapillai *et al*. (2011) studied the drying kinetics of banana (*Nendran spp*) under microwave, convective and combined microwave-convective process, and observed that MD resulted in a substantial decrease in the drying time with quality product when dried at higher power (300W) level compared to other processes. Maskan (2000) reported that higher drying rates observed for products processed by microwaves compared to those of conventionally processed products is due to the internal heat generation caused by microwaves establishing a greater vapor pressure difference between the surface and centre of product, thus increasing the productøs moisture diffusivity.

Solar drying has remained the cheapest means of drying fruits in most developing countries. It is divided into two main types namely direct and indirect. The direct usually called sun drying involves placing the fruit product directly on trays in open air in which only the incident solar radiation is used as the energy source for drying. The indirect means involves the use of mechanical solar dryers which relies on solar energy to heat the drying air and then flows through or over the product by natural or forced convection means. Different designs of these dryers are available in literatures. According to Imre, (1987), Ratti and Mujumdar, (2005), the main advantage of these dryers is that the energy source is renewable, free and non- polluting. Bolin and Salunkhe (1982) reported that drying of apricots to 24% moisture content took 50h under sun drying method as opposed to 31h when a mechanical solar dryer was used. This is an indication that solar drying is a time consuming operation when compared to other types of drying methods. Moreover the use of this method of drying is suitable for regions with tropical climates where hot sun and dry atmosphere exist over a period of time.

Freeze drying technique has been widely used for drying various fruits such as figs, cherries, strawberries and peaches (Shishehgarha *et al.* 2002). Some advantages of freeze drying with respect to the quality of final product as highlighted by Okos *et al* (1992); Jayaraman and Gupta (1992) includes minimal shrinkage of final product, high retention of nutritional value, high flavor and aroma retention coupled with easy rehydration characteristics of the final product. For instance, freeze drying technique for microencapsulation of *Garcinia* fruit extract using three different wall materials such as whey protein isolate (WPI), maltodextrin (MD) and combination of whey protein isolate and maltodextrin as investigated by Ezhilarasi *et al*. 2013 showed that all the three encapsulates yielded higher free (above 85%) and net (above 90%) hydroxylcitric acid recovery. Despite the inherent advantages associated with freeze drying technique, its use is still limited due to the high capital and operating costs involved.

Osmotic dehydration can be defined as a simultaneous counter-current mass transfer process in which biological materials (such as fruits and vegetables) are immersed in a hypertonic aqueous solution for a selected period. The driving force for the diffusion of water from the tissue into the solution is the higher osmotic pressure of osmotic solution and its lower water activity that results in the transfer of water from the product across the cell wall (Azarpazhooh and Ramaswamy 2010a). The diffusion of water is associated with the simultaneous counter diffusion of solutes from the osmotic solution into the tissue. This contributes to a net opposite flux of water and solutes that allow the tissue to become concentrated with a determined ratio solute gain/water loss (SG/WL) depending on process conditions (Chiralt and Fito, 2003). Since the membrane responsible for osmotic transport is not perfectly selective, other solutes (sugar, organic acids, minerals, vitamins) present in the cells can also leach into the osmotic solution (Lenart and Flink, 1984; Torreggiani, 1993) in amounts that are quantitatively negligible compared with the other transfer; however, they are important in terms of final product quality (Azarpazhooh and Ramaswamy 2010a). Pragati *et al.* (2003) conducted an experiment on effect of different drying methods on nutritional composition of dehydrated aonla, and reported that osmo-air drying method was found to be the best, because of the better retention of nutrients after 90 days of storage. Different pretreatments that has been successfully used to enhance osmotic dehydration of fruit includes: ultrasound (Carcel *et al* 2007; Rodriguez and Fernandes 2007; Duan *et al* 2008), blanching (Akyol *et al* 2002; Rahman and Perera 1999), high hydrostatic pressure (Taiwo *et al.* 2001; Akyol *et al.* 2006), pulsed electric field (Taiwo *et al.* 2001; Ade-Omowaiye *et al.* 2001) and microwave (Azarpazhooh and Ramaswamy 2010b).

EFFECTS OF DRYING ON NUTRITIONAL QUALITY OF FRUITS

Food nutrients degrade during drying and the magnitude of change depends on the foodstuff and the drying conditions. As a general rule of thumb, reaction rate increases with temperature and reactant concentration. Losses of nutrients can be minimized by applying suitable pretreatments, selection of appropriate drying methods and optimization of drying conditions (Sablani, 2006). Table 4 gives details of some important pretreatments used prior to drying.

Study of the convective drying of pumpkin (*Cucurbita maxima*) by Guine *et al*. (2011) showed that convective drying at the lowest temperature, 30^{o}C, induces reductions of 14% in proteins, 65% in total sugars and 36% in fiber. Furthermore, the drying temperature seems to have a negligible effect on the nutritional characteristics of the pumpkin, since the results for the drying at 30^{o}C are quite similar to those for the drying at 70^{o}C. Water soluble vitamin C (ascorbic acid) is the most labile component among all the vitamins contained in foods. It is rapidly destroyed by heat at certain pH range and by oxidation (Tannenbaum *et al*. 1985). The effects of both drying temperature and time on ascorbic acid degradation can be presented in terms of the thermal resistance (*D121*), the time at 121^{o}C to decrease concentration of ascorbic acid by 90%. The D_{121} of ascorbic acid is around 100 minutes depending on the a_w, pH, and other factors (Erdman and Klein, 1982). However, Maroulis and Saravacos (2003) reported that D_{121} and z

value (thermal resistance factor), which is the temperature rise required to reduce the decimal reduction time by 90% (one log cycle), is 931 minutes and 17.8^{o}C, respectively. Leung (1987) pointed out that reaction rates of vitamin A, B_1 and B_2 increase with increasing a_w (0.24-0.65) with the B vitamins being more stable than vitamins A and C at various a_w values. Kinetics of ascorbic acid degradation during air drying of whole rosehip (Erenturk *et al*. (2005) showed that changes of vitamin C content during drying was affected by drying time, drying air temperature and moisture content. In addition, the loss of vitamin C was increased depending on the rate of the oxygen in the air CO_2 mixtures used as a drying medium. They further stated that the degradation of vitamin C could be reduced by using an inert gas as drying medium. In the study of effect of different drying conditions on the vitamin C content of kiwifruits, Kaya *et al*. (2010) discovered that increasing drying air temperature causes more loss in vitamin C in the dried fruits while degradation of vitamin C is reduced with increasing relative humidity of drying air. Mrad *et al*. (2012) in the evaluation of quality and structural changes in parallel epipedic pieces of pears during convective drying at different air temperatures (30ï 70^{o}C) observed that ascorbic acid deterioration demonstrated first-order kinetic behavior and was found to depend on air temperature and pear moisture content. Loss of ascorbic acid content increased with increasing air temperature. Possible explanation could be the irreversible oxidative reaction occurring during drying. Evaluation of the effects of different freezing and thawing methods on color, polyphenol and ascorbic acid retention in strawberries (*Fragaria ananassa*) showed that ascorbic acid retentions after thawing were independent of the freezing technology, different thawing procedures significantly affected fruit quality. Maximum ascorbic acid retention was observed when strawberries were thawed in a microwave oven for 10 minutes. Usual thawing at 4°C for

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24 hour caused the most pronounced pigment and ascorbic acid losses. Thus, the thawing regime found to be the key parameter for vitamin C retention of strawberry products (Holzwarth *et al*. 2012).

Most fruits contain various antioxidants which are beneficial to human health such as in lowering incidence of degenerative diseases i.e. cancer, arthritis, arteriosclerosis, heart diseases, inflammation, brain dysfunction and ageing process (Lim *et al*. 2007). This is due to the ability of the antioxidants to scavenge free radicals in human body and thereby decrease the amount of free radical damage to biological molecules like lipids and DNA (Wu *et al.* 2004). Some antioxidants from plant chemical are vitamin C, vitamin E, carotenoids, polyphenols, melanoidins and indoles (Manarch, *et al*. 2004).

Drying causes nutritional losses and hence some antioxidants are destroyed, probably due to thermal degradation, depending on the drying condition and techniques used. Dried fruits have higher total energy, nutrient density, fibre content, and often significantly greater antioxidant activity compared with fresh fruits as a consequence of concentration. The elevated antioxidant activity is mainly due to the concentration of polyphenolics during drying and potentially the generation of Maillard reaction products compounds which can enhance antioxidant activity (Yilmaz and Toledo, 2005). Drying process can also lead to losses in total polyphenolic compounds and changes in ratios of free to total polyphenolics, as shown in six types of dried fruit (Vinson *et al.* 2005; Bennett *et al*. 2011). As such, the net antioxidant activity reflects cumulative effects of total polyphenol losses and production of Maillard reaction products.

Nevertheless, the plasma antioxidant capacity was significantly elevated by the consumption of dried figs, demonstrating bioavailability of antioxidant species (Vinson *et al*. 2005). Holzwarth *et al*. (2012) reported that anthocyanins retention after thawing were independent of freezing technology, different thawing procedures significantly affected fruit quality. Anthocyanins were best retained when strawberries were thawed at 20°C and in a microwave oven, respectively in their study on the effect of drying methods on the antioxidant composition of strawberries.

EFFECTS OF DRYING ON PHYSICAL QUALITY OF FRUITS

Structural collapse in food due to moisture removal from the food product results in significant changes in texture (Yan *et al*. 2008; Ong and Law, 2010). This causes shrinkage and change in porosity of the dried fruit products. Texture attributes such as hardness, fracturability, springiness, chewiness, gumminess, cohesiveness and resilience can be determined by texture profile analyses. Apple slices dried by two combinations, microwave vacuum drying (MWVD) methods and by freeze-drying (FD) were analyzed for texture as investigated by Huang *et al.* (2012). They reported that the crispness of FD + MWVD samples was higher than MWVD + FD samples and the hardness of FD + MWVD samples was lower than MWVD + FD samples. According to Deng and Zhao, (2008) freeze-dried apples showed softer texture when compared to hot air drying in their study on effect of pulsed vacuum and ultrasound osmo-pretreatments on glass transition temperature, texture, microstructure and calcium penetration of dried apples (Fuji variety). Study on the drying kinetics of nopal (*Opuntia ficus-indica*) using three different methods and their effect on their mechanical properties revealed that convective drying have more cohesiveness than samples treated solely by osmotic drying. On the other hand, samples treated by osmotic drying became more elastic (Torres *et al*. 2008). This is an indication that osmotic treatment of fruits before drying could be a potential means of preserving the mechanical structure of fruits.

It is an established fact that peopleôs perception of the flavor of many dried fruit products can be influenced by their color (Clydesdale, 1993; Morrot *et al.* 2001; Philipsen *et al.* 1995; Zellner and Durlach, 2003). Evaluation of color can be carried out by using destructive or by non-destructive methods. Destructive method is carried out by evaluating the extracted color pigments spectrophotometrically or by using high performance liquid chromatography (Topuz, 2008). Alternatively, the non-destructive method can be used using the CIELAB color space (L*a*b*) (Abbot, 1999). It has proven valuable in describing visual color deterioration and providing useful information for quality control in various fruits and vegetables during drying such as kiwifriut (Maskan, 2001), banana and guava (Chua *et al.* 2002) and mango pulp (Jaya and Das Gupta, 2003).Futhermore, modeling of color change has also been made possible through the use of model or equations available in literatures. Some equations for modeling color change as developed by Ponkham *et al.* (2012) are shown in Table 5.

Color, of some fruits dehydrated by a combination of different methods as investigated by Chong *et al*. (2013) showed that for apple, pear and mango the total color change of samples dried using continuous heat pump (HP) or heat pump vacuum-microwave (HP/VM) methods was lower than that of samples dried by other combined methods. For papaya, the lowest color change was exhibited by samples dried using hot air-cold air (HHC) method and the highest color change was found for heat pump (HP) dehydrated samples. Sensory evaluation revealed that dehydrated pear with higher total color change was found to be more desirable because of its golden yellow appearance. Ratti (2001) provided a comparison of changes in color during air drying and freeze-drying of strawberries at different temperatures. Changes in the color of air dried samples were significantly higher compared to freeze-dried ones. Discoloration and browning during air drying may be the result of various chemical reactions including pigment destruction (Garcia-Viguera *et al*. 1998; Krokida *et al.* 1998). The total color change of dried Chempedak was found to increase at different drying temperatures of 50, 60, and 70^{o}C (Chong *et al*. 2008). The effects of different hot air drying temperatures (50 to 80^{o}C) and sun drying on color values of apricot (*Prunus armenica* L.) as carried out by Karabulut *et al*. (2007) showed that color values of hot air dried samples was favorable in comparison to sun drying.

Volume shrinkage in biological materials has been found to be a function of moisture content (Abbasi *et al.* 2008; Hashemi *et al*. 2009). Kingsly *et al*. (2007) and Janjai *et al*. (2010) observed that shrinkage occurred in relation with the amount of removal of moisture from fruits in their studies on shrinkage of ber (*Zizyphus mauritian* L.) fruits during sun drying and diffusivity, shrinkage and simulated drying of litchi fruit (*Litchi chinensis* Sonn.) respectively. Heating and loss of water cause stresses in the cellular structure of the food and this leads to changes in shape and a decrease in dimensions (Mayor and Sereno, 2004). When moisture is removed within the solid network of a food product during drying, a pressure unbalance is produced between the inner and external part of the food material, generating contracting stresses that lead to material shrinkage, changes in shape and sometimes product cracking (Mayor and Sereno, 2004).

Shrinkage of food products during drying can be modeled using empirical or fundamental relationships. In empirical modeling, shrinkage, volume, area or thickness is a function of moisture content or moisture ratio in most models. Empirical models are suitable for materials with very low porosity or materials with uniform porosity development during drying. In contrast, the fundamental models are derived based on mass balance, density and porosity (Ong and Law, 2010). Three different types of shrinkage have been reported during drying: one dimensional, isotropic or three dimensional and anisotropic or arbitrary (Araya-Farias and Ratti, 2009). Recently linear and quadratic models were developed by Ponkham *et al*. (2012) to model the combined infrared radiation and air drying of a ring shaped-pineapple with regards to shrinkage. They concluded that the quadratic model was better than the linear model to predict shrinkage kinetics for all four dimensions namely outer radius, inner radius, thickness and volume of pineapple rings and as well applicable to other fruit types. Table 5 also highlights some mathematical models for predicting shrinkage as developed and used by different authors.

The measurement of shrinkage is carried out based on the displacement methods to determine its apparent volume. Comparison of shrinkage measurement methods during drying of banana, pineapple and mango slices was reported by Yan *et al*. (2008) using: displacement with glass beads, liquid displacement, liquid pycnometer and Archimedes principle. The Archimedes method using solvent n-heptane was recommended based on the lowest coefficient of variation. The greater difference between the density of the solvent and sample enables n-heptane to distinguish the finer difference of sampleȏs weight between in the air and solvent.

Porosity is a measurement of pore or empty spaces of a material to that of the total volume or simply it can be defined as the volume fraction of air in the food product. Transport, mechanical and textural properties are affected by porosity (Hussain *et al*. 2002; Chen, 2008). Glass transition theory is one of the concepts that are used to explain changes in porosity during drying. Generally, structural collapse is negligible if the food material is processed below glass transition temperature (Tĝg). The higher the difference between the process temperature and the glass transition temperature, the higher is the collapse (Rahman, 2001). This is the reason why freeze dried material (T < Tĝg) is generally more porous with negligible shrinkage as compared to hot air dried material. In addition, surface tension, structure, environment pressure and mechanisms of moisture transport equally play significant roles in porosity development (Ong and Law, 2010). Study on the porosity of banana, pineapple and mango slices during air-drying revealed that porosity of banana and mango slices increased 3-folds up to 17% wb and 5- folds up to 12% wb from fresh sample, respectively while that of pineapple increased with moisture content of dried pineapple from around 6% wb to 33% wb, and then kept decreasing till raw pineapple (Yan et al. 2008). Bai *et al*. (2002) studied the structure of heat pump dried apple rings under air temperature (20, 40 and 60^{o}C) and a constant humidity, by porosity measurements and scanning electron microscopy. They reported that porosity of the apple rings increased linearly with drying time.

According to Khalloufi *et al.* (2009) several mathematical expressions have been suggested to predict the porosity as a function of moisture content. A model to predict porosity is included in table 5. These models can be grouped in two categories: (i) theoretical models that are built based on the understanding on the fundamental phenomena and mechanisms that may be involved in pore formation; (ii) empirical models that are built by fitting the modelôs parameters to the experimental data. Note that the fitting parameters of the theoretical models have a physical meaning, while those involved in empirical models do not provide any. Although the empirical models give globally a good fitting of the experimental data, they offer limited insight into the fundamental principles involved, hindering the understanding of the mechanisms that are responsible for water removal. The main drawbacks of these empirical approaches are: (i) the fitting parameters do not have any physical meaning, which limits the interpretation of data and hinders the understanding on the governing mechanisms in water removal; and (ii) these models are not generic as they depend on the product, the drying technology and the processing conditions such as temperature, pressure, humidity, and air speed (Madiouli *et al*. 2007; Rahman, 2001). Methods such as helium stereopycnometry (Krokida and Maroulis, 1997), mercury porosimetry (Karathanos *et al.*, 1993) and the measurement of the volume of ground and degasified samples (Nieto *et al*. 2004) have been used determine the porosity of food materials. Sereno *et al.* (2007) proposed a non-destructive method based on gas pycnometry to determine the particle density and porosity of foods and materials with high moisture content. Moreover, the measurement of the porosity of foods can be accomplished by image processing, using either an image from a microscope or, in the case of macroporous foods, an image directly captured from a video camera and macro lens (Barret, 2002).

Rehydration is a complex process aimed at the restoration of previously dried materials in contact with water. It is generally accepted that the degree of rehydration is dependent on the degree of cellular and structural disruption (Falade and Abbo, 2007). During dehydration, irreversible rupture and dislocation occur resulting in loss of integrity and hence a dense structure of collapsed, greatly shrunken capillaries with reduced hydrophilic properties as reflected by the inability to rehydrate fully (Lewicki, 1998). Pre-drying treatments and drying operation induce changes in structure and composition of plant tissues, which could result in impaired rehydration properties (Lewicki, 1998). In a first order kinetic model used by Krokida and Marinos-Kouris (2003) to model the rehydration kinetics of various dried fruits and vegetables, the water temperature was found to influence the rehydration rates and the equilibrium moisture content in a positive way. Rehydration behaviors of five freeze-dried fruits, namely, pineapple, mango, guava, acerola and papaya as investigated by Marques *et al*. (2009) reported that the rehydration of the freeze-dried fruits involved a high water uptake rate at the early stage of the process followed by a decreased rate and finally approaching saturation condition. Mango, papaya and pineapple presented the higher rehydration rates as compared to acerola and guava, which, on the other hand, had higher rehydration ratio at saturation. Rehydration and properties of osmotically pretreated freeze-dried strawberries investigated by Agnieszka and Andrzej (2010) reported a decrease in rehydration capacity and adsorption rate of freeze-dried strawberries that were osmotically dehydrated in sucrose and glucose solution. Lewicki, (1998) also reported that pretreatments could actually have effect on the rehydration characteristics of fruits.

The moisture migration process during drying is complex and often involves one or more transport mechanisms such as liquid diffusion, vapor diffusion, Knudsen diffusion, surface diffusion and hydrostatic pressure differences (Mujumdar and Devahastin, 2008). The term effective diffusivity is used to describe the rate of moisture movement, no matter which mechanism is involved. In most cases, the total diffusivity is the sum of the vapor phase and liquid phase diffusivities. Generally, diffusivity values fall between 10^{-13} and 10^{-6} m^2 s^{-1} while most values (92%) fall within 10^{-12} and 10^{-8} m^2 s^{-1} (Zogzas *et al*. 1996). Table 6 is a list of effective moisture diffusivity values of some fruits as affected by different drying temperatures. Methods of determining effective moisture diffusivity of foods includes sorption kinetics, permeation method, concentration distance curves, radiotracer methods, nuclear magnetic resonance, electro spin resonance and simplified methods (Crank and Park, 1968; Naesens *et al*. 1981; Gross and Ruegg, 1987; Marinos-Kouris and Maroulis, 2006).

At high temperature the water molecules are loosely bound to the food matrix, thus requiring less energy to remove than at lower temperature (Tunde-Akintunde and Ogunlakin, 2011). Low porosity materials effective moisture diffusivity values is very close to liquid diffusivity while for granular and porous materials moisture is transported mainly by vapor diffusion through the void space, an indication of the effect void fraction on effective moisture diffusivity values (Karathanos *et al*.1990; Aghbashlo *et al*. 2008). Influence of drying conditions on the effective moisture diffusivity during the thin layer drying of berberis fruit (*Berberidaceae*) as investigated by Aghbashlo *et al.*(2008) showed that the value of effective moisture diffusivity varied from 3.320×10^{-10} to 9×10^{-9} m^2/s and that increase in air temperature at constant air velocity increased the value of effective moisture diffusivity whereas the increase in air velocity at constant air temperature decreased the value of effective moisture diffusivity. The effective diffusivity of banana slices estimated by the optimization technique as carried out by Thuwapanichayanan *et al*. 2011) was found to decrease sharply with moisture content in the first falling rate period and changed slightly in the second falling rate period. In addition Caglar *et al*. (2009) equally stated that moisture diffusivity increases with decrease in moisture content and with increase in temperature. The effective moisture diffusivity of pretreated and untreated pumpkin as investigated by Tunde-Akintunde and Ogunlakin (2011) revealed that moisture diffusivity varied from a minimum of 1.19×10^{-9} m^2/s for untreated pumpkin samples dried at 40°C to a maximum value of 4.27×10^{-9} m^2/s for steam blanched samples dried at 80°C. Zielinska and Markowski (2010) reported that volumetric shrinkage significantly influences moisture diffusivity of wet materials and that shrinkage should be taken into consideration during modeling the drying process of food products. The effective moisture diffusivity values of sweet cherries as affected by pretreatment solution and air temperature are were found to be between $5.683\times10^{ï\,10}$ and $1.544\times10^{ï\,9}m^2/s$ (Doymaz and Ismail, 2011). A summary of the effects of drying on some physical properties of fruits is shown on table 7.

EFFECT OF DRYING ON SENSORY PROPERTIES OF FRUITS

Sensory evaluation is a method of accurate measurement of human responses to foods with minimal biasing effects (Ong and Law, 2010). Elortondo (2007) developed an accredited sensory method for the quality evaluation of foods. Most sensory attributes can be correlated to the physical and chemical properties of the food product. Leite *et al*. (2007) reported that lower drying temperatures produced better-accepted dried banana products in their study on effect of drying temperature on the quality of dried bananas cv. *prata* and *d'a´gua.* According to

Shigematsu *et al.* (2005), sensory analysis of star fruit showed that star fruits pretreated with osmotic dehydration were more accepted by consumers regarding appearance, texture, and flavor than air-dried star fruits and star fruits that were pretreated with a mixture of sucrose and $CaCl_2$. Air-dried star fruits had the lowest scores for appearance, texture, and flavor. Acceptance was also higher when air drying was carried out at 60°C rather than at 70°C. Szczesniak (2002) correlated sensory and instrumental ratings for hardness, chewiness, adhesiveness, brittleness, gumminess and viscosity. Dried food with high fat content can easily become rancid due to fat oxidation. Oxygen level below 1% is effective in delaying rancidity, staleness and other deteriorative activities in dried food product (Perera, 2005). Influence of processing conditions on flavor compounds of custard apple (*Annona squamosa* L.) as investigated by Shashirekha *et al*. (2008) showed that heating fresh pulp at 55 and 85^{o}C, tend to produce increased flavor spectrum, the compounds relatively being more at 85^{o}C. At 55^{o}C, significant increase in the quantities of Ǖ-pinene, ɓ-pinene, linalool, germacrene and spathulenol were observed; higher quantities of cineole, limonene, Ǖ-cubebene and Ǖ-copaene, caryophyllene, Ǖ-farnecene and ŭ-cadenene were formed, while these were totally absent in fresh pulp. Significant increase in quantities of Ǖ-pinene, ɓ-pinene, 1, 8-cineole, limonene, aromadendrene, Ǖ-farnecene, ɔ-cadenene, ŭ-cadenene and spathulenol were found by heating pulp at 85^{o}C. Spray-dried samples, showed increased flavor note with the use of whole milk powder as compared to the skim milk powder. This is an indication that drying of fruits at lower temperatures could have a beneficial effect on fruits in terms of flavor.

EFFECT OF DRYING ON MICROBIOLOGICAL AND SHELF STABILITY OF FRUITS

Enzymatic reactions can occur in low moisture foods if the enzymes are not inactivated by heating. Hence, reduction of water activity in final product is a very important mean to ensure the stability of the dried foods. Final product with sufficient low water activity is safe from enzymatic spoilage in general because active water is not available for microbial growth (Chieh, 2006). Study of inactivation of *Wisteria monocytogenes* during drying and storage of peach slices treated with acidic or sodium metabisulfite solutions showed that after 6 h of dehydration, populations on control or water immersed slices were reduced by 3.2ï 3.4 log cfu/g, whereas populations on slices treated with sodium metabisulfite or acidic solutions were reduced by 4.3ï 5.1 log cfu/g and 5.3ï 6.2 log cfu/g respectively (DiPersio *et al.* 2004). The effect of hot air treatment at 38ŬC for 36 h in combination with *Pichia guilliermondii* on postharvest anthracnose rot of loquat fruit revealed that the combined treatment significantly reduced natural decay, and disease incidence and lesion diameter in artificially inoculated fruit (Liu *et al*. 2010). Fruit given the combined treatment maintained low activities of catalase during the early storage period, but catalase and superoxide dismutase activities both rose later in storage. According to Machado *et al*. (2010), using moderate electric fields below 25^{o}C showed that electric fields above 220 Vcm^{-1} greater electric fields, while presumably overcoming the thermal degradation caused by conventional high temperature treatments.

The removal of moisture content reduces the water activity (a_w) of a product during drying. In general, a_w in most dried fruit is relatively low, typically less than 0.6, which is the

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recommended level for safe storage (Ong and Law, 2010). Low a_w inhibits the growth of various microorganisms and prevents oxidation and enzymatic reactions in fruits (Rahman, 2005). Drying coupled with proper packaging and storage play an important role in affecting the shelf life of a fruit product. Typically the optimum relative humidity for dried product storage is 55 ï 70% at moisture content ranging from 2 to 20% (Perera, 2005). Packaging should be moisture proof and able to prevent the transfer of oxygen into the product and cause off flavor formation. Alternatively, modified atmosphere packaging technique can be used to extend the shelf life of the dried products (García-Esteban *et al*. 2004).

CONCLUSION

Drying operations in recent years have made possible the production of various value added and convenience foods. It helps to extend shelf life, minimize loss, and prevents growth of microbes. However, drying as a means of processing and preserving fruits, if not properly applied could have adverse effects on fruits quality properties such as nutritional quality, shrinkage, porosity, rehydration ability, microbiological stability and sensory properties such as flavor, color, taste, and texture. Since most fruits are amenable to drying, it is important that the effect of drying on fruits quality parameters and indices be minimized and this could be achieved by using a drying system which minimizes the exposure of fruits to light, oxidation and heat. Proper selection of dryer/pretreatments for the preservation of fruits is therefore required if this aim must be achieved. Freeze drying coupled with suitable pretreatment such as potassium carbonate could be used to achieve this aim due to its minimal effect on quality indices of dried fruit products.

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Table 1. Polyphenols in fruits

Class	**Fruit**	**References**
Phenolic acids: Hydroxycinnamic and Hydroxybenzoic acids	Stone fruits: Plums, Peaches, Sweet Cherries, Nectarines, Sour cherries, Apricots Star fruit, Papaya Orange, Black Currant, Blueberry, Pear, Kiwifruit, Passion fruit, Peach, Blackberries, Whortle berries, Raspberries, Strawberries,	Heinonen & Meyer, (2005); Tomas-Barberan *et al.* (2001); Gavrilova *et al*. (2011); Fu *et al*. (2011); Golukcu & Ozdemir (2010); Kelebek & Selli (2011a)
Flavonoids: Flavonols, Flavanones, Flavan-3-ols, Flavones and Anthocyanins	Grapefruit, Blackcurrant, Blueberry, Lemon, Pineapple, Plum, Watermelon, Orange Red grape, Sweet cherry Passion fruit, Jackfruit, Pomegranate, Camu-camu, Apple, Mango, Durian, Bilimbi fruit, Raspberry, Pomegranate, Acerola	Fu *et al*. (2011); Obon *et al*. (2011); Fuzfai & Molnar-Perl (2007); Iacopini *et al*. (2008); Kelebek & Selli (2011b); Zhang *et al*. (2011) ; Plaza *et al*. (2011); Akter *et al*. (2011); De Ancos *et al*. (2011); Heinonen & Meyer , (2005); Poovarodom *et al*. (2010) ; Miean & Mohamed (2001); Fanali *et al*. (2011); Mamede *et al*. (2009)
Stilbenes	Red Grape, Cranberry, Strawberry	Granato *et al*. (2011); Huang & Mazza (2011)

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Table 2. Glycemic index of some fruits

Fruit	Raw	Dried
Apple	40-44	29
Apricot	34-57	30-32
Banana	46-70	N/A
Mango	41-60	N/A
Orange	31-51	N/A
Peach	28-56	35
Pear	33-44	43
Pineapple	43-66	N/A
Plum	39	29

Source: http://www.glycemicindex.com/foodSearch.php. Carbohydrate containing foods are classified as high; GI > 70, moderate; 56 ï 69, or low; 0 ï 55 (GI Database, 2011).

Table 3. Some fruit drying methods

Drying method	**Fruits**	**Reference**
Vacuum	Dates	Amellal and Benamara (2008)
Microwave	Strawberry, Banana, Cranberries	Piotrowski *et al.* (2004); Krokida and Maroulis (1999); Sunjka *et al*. (2004); Ganessapilai *et al*. (2011); Sousa and Marsaioli, (2004)
Heat pump	Nectarines, Guava, Papaya	Jangam *et al*. (2008); Sunthonvit *et al*. (2007); Hawlader *et al*. (2006)
Freeze	Barbados cherry, Guava, Papaya, Mango	Marques *et al*. (2006)
Spray	Bayberry	Gong *et al*. (2008)
Spouted bed	Mango pulp	Cunha *et al*. (2006)
Fluidized bed	Aonla	Murthy and Joshi (2007)
Solar	Longan, Prickly pear fruit	Janjai *et al*.(2009); Lahsasni *et al.* (2004)
Oven	Banana, Pineapple, Mango	Abano and Sam-Amoah (2011); Yan *et al*. (2008); Leite *et al*. (2007); Ganessapilai *et al*. (2011)
Cabinet tray	Banana	Demirel and Turhan (2003)

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Table 4. Pretreatments used prior to drying of fruits.

Pretreatment	References
Blanching	Lewicki, (2006)
Skin Puncturing	Lewicki, (2006)
NaOH	Shi *et al*.(1997); Pangavhane *et al*. (1999); Carranza-Concha *et al*. (2012); Dev *et al.* (2008); Vásquez-Parra *et al*. (2013)
K_2CO_3	Pangavhane *et al*. (1999); Vásquez-Parra *et al*. (2013)
Surface abrasion	Lewicki, (2006)
Ethyloleate	Shi *et al.*, (19970; Lewicki, (2006); Di matteo *et al.* (2000)
Olive oil	Pangavhane *et al*. (1999); Vásquez-Parra *et al*. (2013)
Sulfiting	Togrul and Pehlivan, (2004); Lewicki, (2006)
Osmotic treatment	Lenart *et al.*1993; Lewicki and Ğukaszuk, (2000); Lewicki, (2006)
Immersion in acid solutions	Yohan-Yoon *et al.,* (2004); Calicioglu *et al.* (2002)

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Table 5. Mathematical models for predicting shrinkage, moisture diffusivity, color, and porosity during drying

Model	**Geometry**	**Parameter**	**References**
V_r=aX+b	Cylinder Sphere	Shrinkage	Ratti (1994) Mclaughlin and Magee (1998)
V_r=a+bX+cX^2+dX^3	Cylinder	Shrinkage	Ratti (1994)
V_r=aexp(bX/X_o)	Cylinder & slab	Shrinkage	Mayor and Sereno (2004)
A/A_o=(V/V_o)$^{2/3}$	Cube	Shrinkage	Suzuki *et al*. (1976)
V_r=1/(1ī Ǘ(1+ɉ$_o$(x-x_o)/ɉ$_w$(1+x_o)ī Ǘ$_0$	Cylinder	Shrinkage	Mayor and Sereno (2004)
$S = a + b(M/M_0)$	Linear	Shrinkage	Ponkham *et al*. (2012)
$S = a + b(M/M_0) + c(M/M_0)^2$	Quadratic	Shrinkage	Ponkham *et al*. (2012)
$X = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{2n-1}\exp\left[-\left(2n-1^2\right)\frac{\pi^2}{4b}\left(\frac{D_L t}{b}\right)\right]$	Cylinder & slab	Moisture diffusivity	Pakowski and Mujumdar, (1995)
ǔ$E = at^2 + b\,t + c$	Quadratic	Color	Ponkham *et al.* (2012)
ǔ$E = a\,t^3 + b\,t^2 + c\,t + d$	Cubic	Color	Ponkham *et al*. (2012)
$\varepsilon = 1-\frac{\rho}{\rho_s}\left(\frac{1+\beta X}{1+X}\right)$	____	Porosity	Martynenko, (2008)

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$S = r_o$ for outer radius shrinkage, $S = r_i$ for inner radius shrinkage, $S = l$ for thickness shrinkage, $S = V/V_0$ for volume shrinkage and *a*, *b*, *c*, *d*, *e*, *f*, *k* and *n*, are model constants, *t* is time (h), ɓ = density ratio coefficient, X = moisture content (kg/ kg^{-1} dry basis), ɟ = bulk density (kg/ m^{-3}) , s = solid, ǔE is the total color difference.

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Table 6. Effective moisture diffusivity values of some fruits

Fruit	**Temperature °C**	**Diffusivity m^2/s**	**References**
Berberis fruit	50-70	3.320×10^{-10} - 9×10^{-9}	Aghbashlo *et al*. (2008)
Untreated Pumpkin	40	1.19×10^{-9}	Tunde-Akintunde and Ogunlakin, (2011)
Steam blanched Pumpkin	80	4.27×10^{-9}	Tunde-Akintunde and Ogunlakin, (2011)
Litchi	50-80	4.832×10^{-10}-15.323×10^{-10}	Janjai *et al*. (2010)
Apple	30 - 70	1.0×10^{-11} - 3.3×10^{-9}	Zogzas *et al*. (1996)
Banana	20-40	3.0×10^{-13} - 2.1×10^{-10}	Marinos-Kouris and Marouris (1995)
Persimmon slices	50-70	7.05×10^{-11}-2.34×10^{-10}	Ibrahim Doymaz, (2012)
Grape	50-80	$2.09 \times 10^{\bar{\imath}\ 11}$-$5.39 \times 10^{\bar{\imath}\ 10}$	Caglar *et al*. (2009)
Avocado	30-58	3.3×10^{-10} - 1.2×10^{-9}	Jangam and Mujumdar, (2010)
Chestnut	70-90	4.45×10^{-9}- 7.65×10^{-9}	Guine´and Fernandes, (2006)
Amelie and *Brooks* mangoes	40-60	2.79×10^{-11} - 1.84×10^{-10}	Dissa *et al*. (2011)
Plum	55-65	3.04×10^{-10} - 4.41×10^{-10}	Goyal *et al*. (2007)

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Table 7. Effect of drying on physical quality of dried fruits

Physical attribute	**Drying effect**	**Reference (s)**
Color	Increase with increase in air temperature	Chong *et al*. (2008); Karabulut *et al*. (2007)
Texture	Increase with elevated air temperature	Deng and Zhao (2008); Huang *et al*. (2012)
Shrinkage	Increase with increase in rate of moisture removal/loss, drying time and air temperature	Abbasi *et al*. (2008); Hashemi *et al*. (2009); Yan *et al*. (2008); Janjai *et al*. (2010)
Porosity	Increase with increase in drying air temperature, time and rate of moisture removal.	Yan *et al*. (2008); Khalloufi *et al*. (2009); Bai *et al*. (2002)
Effective moisture diffusivity	Increase with increase in drying air temperature	Caglar *et al.* (2009); Aghbashlo *et al*. (2008); Tunde-Akintunde and Ogunlakin (2011); Doymaz and Ismail (2011)
Rehydration	Increase with decrease in the rate of cellular and structural disruption	Falade and Abbo (2007); Krokida and Philippopoulus, (2005)


Dried Longan fruit
Dried Date fruit
Dried Mango slices
Dried Jackfruit
Dried Banana rings
Dried Apple slices
Dried Prunes
Dried Kiwifruit
Dried Orange slices
Dried Pear fruit
Dried Plums

Figure 1. Dried fruits. Source:

http://www.google.co.za/search+images+and+photos+of+dried+fruit+products

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