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Food Structure: Its Formation and Relationships with Other Properties

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Food materials are complex in nature as it has heterogeneous, amorphous, hygroscopic and porous properties. During processing, microstructure of food materials changes which significantly affects other properties of food. An appropriate understanding of the microstructure of the raw food material and its evolution during processing is critical in order to understand and accurately describe dehydration processes and quality anticipation. This review critically assesses the factors that influence the modification of microstructure in the course of drying of fruits and vegetables. The effect of simultaneous heat and mass transfer on microstructure in various drying methods is investigated. Effects of changes in microstructure on other functional properties of dried foods are discussed. After an extensive review of the literature, it is found that development of food structure significantly depends on fresh food properties and process parameters. Also, modification of microstructure influences the other properties of final product. An enhanced understanding of the relationships between food microstructure, drying process parameters and final product quality will facilitate the energy efficient optimum design of the food processor in order to achieve high-quality food.

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Keywords

Microstructure, drying, heat and mass transfer, food quality, drying parameters

INTRODUCTION

One of the most important concerns in the food drying process is the quality attributes of dried food. Physical, chemical and nutritional characteristics of food material undergo modification due to extensive moisture removal process during drying. Several attempts have been made to find out the most dominant factors that affect the quality of the processed food (Aguilera, 2000;Aguilera, 2005;Karim and Hawlader, 2005a). Particularly, the influence of different drying process parameters including air temperature, air velocity, moisture content of food material have been extensively investigated in the past. However, there has been little investigation on changes in food microstructure during drying and its impact on the finished food. An appropriate understanding of the microstructure of the raw food material and its evolution during processing is critical in order to understand and accurately describe dehydration processes. Evolution of food microstructure is one of the complex arenas that is not yet well understood as it involves material changes, including alterations of the tissue and cell wall structure throughout growth and during drying processes (Charles et al., 2000). Foods generally encompass unstable structures bounded by relatively weak forces. It is a challenge to understand the dynamics associated with structure formation during growth of fresh food (Ramana et al., 1992;Kidmose and Martens, 1999;Aguilera, 2006 ;Vincent 2008) , at different aggregation state (Mezzenga et al., 2005)changes in the structure during the self-life (Man, 2004), structural collapse during consumption (Lucas et al., 2002) and finally process engaged in digestion of food product (Armand et al., 1999). The knowledge of microstructural properties of food materials is important for an optimum design and control of food processing operations as well as for improvement in the quality of the final product.

Preserving the original structure is a major concern, since changes in structure during processing, storage and distribution can lower the quality of finished products (Aguilera et al., 2000).

This article provides a comprehensive review of the factors that impacts food microstructure and its relationship with other food properties. It is explored how physicochemical, functional, and technical attributes of food are connected with its structure and changes in the structure during drying. Role of food compositions in food structure is reviewed first. Following this, changes of microstructure due to food drying is covered. Finally, discussion on the impact of microstructure changes during drying on the other properties of food materials is presented.

FORMATION AND EVOLUTION OF FOOD STRUCTURE

Fresh food properties and drying conditions significantly influence the product structure changes during drying. In this section, a brief discussion on fresh food compositions and food structure is first presented and then microstructure changes during drying has been investigated.

Food composition and structure

Original food compositions play significant roles in structure, stability, and nutritional value of a processed food. Most foods can be treated as complex colloidal multiphase systems (Aguilera, 2006), composed of diverse aggregation states like liquid or solid, crystalline or glassy or even liquid crystalline.

Cellular structure of food

A diverse range of definition of microstructure can be found in the literature. In this study microstructure is defined as the spatial arrangement of elements and their interactions in food material (Heertje 1993). Foods, in general, are mainly composed of polymers and water, where the available polymers are mainly three basic macromolecules (proteins, polysaccharides, and lipids) made up of even simpler repeating units. Food materials also contain minerals and air which all contribute to the development of complex structures in foodstuff. Complex food structures are formed, not as a result of the abundance of elemental components, but as a result of the multiple interactions that proteins and polysaccharides undergo at different conditions in an aqueous medium (Aguilera and Stanley, 1999).

Generally, the living tissue consists of fine organized cellular structure to attain its overall functionality (Ilker and Szczesniak, 1990). Structures of food created in nature may be classified into four broad categories (Parada and Aguilera, 2007), namely- fiburous structure of animal and plant tissue, fleshy material from plants, encapsulated embryos of plants and structure of dairy products

Natural as well as processed foods encompass hierarchical structure and span scales from nano to millimetres as shown in Fig. 1. From cellular to tissue level, different food materials show significantly different structure. This variation of structure causes completely dissimilar reaction during different food processing.

Figure 1 can be inserted about here

It is assumed that higher level structures are progressively assembled from the molecular to the macro scale until the desired properties and functions are achieved (Baer et al., 1991). Cellular materials, for example, organised from glucose to tissue level with size of nano to macro scale. A similar pattern can be found, as shown in Fig. 1, in other types of food structures including crystalline, fibrous and gel.

The cell is the building block of all plant tissue. Cell structure varies in the range of largely honeycomb, such as cells of wood, and closed-cell such as parenchyma cells of fruits and vegetables (i.e. Apple and potato). However, composition of these two diverse cellular structures also can be found in palm stems (Gibson, 2012). Cells integrating with cell walls form tissue matrices which then stabilized with the assistance of fibres. Plant cell wall encompasses cellulose (fibres), hemicelluloses and the matrix pectin and few proteins. Pectin present in cell wall is soluble and water from the cell migrates to the intracellular spaces through it. In addition, the solubility of pectin plays significant role to preserve the intact nature of the cell wall. For example, during the time of ripening most of the plant cell walls swells noticeably according to the degree of solubilisation of the pectin (Redgwell et al., 1997). In many cases, during ripening of fruits, pectin enables to absorb more water, swell more, and consequently lose the adhesive properties and strength. Apple cell, for instance, become spherical instead of polygonal as a result of migration of water through the above process (Aguilera and Lillford, 2008).Therefore, macroscopic structural behaviour depends on turgor pressure, cell wall properties and cell size (Rojas et al., 2002;Aguilera and Lillford, 2007;Alamar et al., 2008).Among these, cell wall components are the key structural components of plants tissue as the mechanical properties of tissue depends on the cell wall properties (Vincent 2008;Joardder et al., 2014).

Role of different compositions of food in structure formation

Composition of food materials plays noticeable roles in the structure, physiochemical stability and nutrition. To be more precise, nature of food polymer mixture mainly determine the structureï properties interrelationships (Tolstoguzov, 2006). In most of the food materials, the main construction biopolymers are polysaccharide and protein, while water act as main plasticizer and solvent. Water in plant based tissue plays the role of plasticizer; therefore, absorbance or loss of it considerably affects the mechanical features of cell walls and eventually the structure of cellular solid foods. Among different types of cells in plant cells, parenchyma cells, as shown in Fig. 2, are typically thin-walled and are present abundantly in the plant food materials. Vacuoles, which serve as cell water storage container, are located inside these cells. Vascular solutes are usually osmotically active, which pushes the cell membrane alongside the cell wall. Consequently, the turgor pressure develops and that keeps the cells in a state of elastic stress and maintains the shape, firmness and crispness of tissue (Ilker and Szczesniak, 1990). If the turgor pressure is lost, the structure of the fruit collapses. Once the natural turgidity is lost it cannot be refurbished (Reeve, 1970).

Figure 2 can be inserted about here

Water has a heterogeneous spatial distribution inside foods, as shown in Fig. 2 (b), and exhibit significant variations in the properties and reactivity depending on molecular environments. Heterogeneous nature of foods is the consequence of presence of different proportion of bulk, capillary, physically bound and chemically bound water. Taking all the types of water as well as their amount and bonding intensity into consideration, present authors have developed a conceptual pyramid for clear understanding of the proportion and characteristics of cell water and presented in Fig. 3.

Figure 3 can be inserted about here

In a broad classification, water in food materials can be classified as free and bound water. Sometime these are also treated as multilayer and monolayer water. In addition, on the basis of spatial position of water, it can be termed as intercellular and intracellular water (Joardder et al., 2013a), as demonstrated in the Fig. 3. Water inside cells is known as intracellular and the intercellular water is that which is present in the capillaries. Apart from water, amount of polysaccharides and protein, and nature of their interaction significantly influence of the structure of food stuff (Aguilera and Lillford, 2008). Polysaccharides are plainly poly-sugars produced by linking together one or more sugars in a variety of ways. The types of sugars and the nature of the linkages determine the structure and function of the polymer.

Baer et al.(1991) Considerable amount of work can be found in the literature concerning influence of the type of sugars, the glycoside linkage and the arrangement of sugars within the polymer on polysaccharide structure. Polysaccharides are important for their three major roles: energy reserve (starch), water stabilization (gums), and structure (cellulose) (Aguilera and Stanley, 1999).

In general, proteins can be classified based on their functionalities of (i) building materials for physical structures, (ii) chemical activity (e.g., enzymes, transport proteins, etc.), and (iii) storage of nutrients. Proteins or polysaccharides are the main determinants of the texture of semi-solid food products. Damoderan et al.(1996) reported that proteins are heat sensitive and change of which alters the solubility and texture of foods. On such occurrence, protein can interact with various food components, which may cause changes in texture. In addition, protein microstructure in raw and processed food influences the physiochemical and sensory properties of food (Bhapatkar et al., 2012). Literature provides evidence that protein microstructure network influences the texture development in food (Hernando et al., 2000).

Lipid may contribute to enzymatic hydrolysis during the initial phase of drying, which may cause change of flavour (Nejad et al., 2003). Changes in the functionability of lipids can take place depending on the alternation of microstructure or other physiochemical properties of foods that contain lipid (Decker et al., 2008).

Micro-macro structural feature of foods

Most of the materials subjected to drying process can be treated as the hygroscopic, porous and amorphous media with the multiphase transport of heat and mass (Srikiatden and Roberts, 2007). Foods, in general, can be considered hygroscopic although there are some exceptions. Due to this hygroscopic nature of food material, once all free water is migrated, it is very difficult to remove bound water from food material. Migration of this bound water requires more energy and may cause severe damage to overall food quality depending on the drying process. In nonï hygroscopic materials the amount of physically bound water is insignificant. (Karel and Lund, 2003). This hygroscopic nature of food leads to inconsistent structure modification throughout the drying process.

In addition, most of the plant based food materials contains its constituents in amorphous state. Therefore, it is essential to keep this state intact in order to retain the flavour, taste and colour of the fresh food materials (Roos, 1995). However, crystalline structure is important for appearance, texture, shelf life and quality of many food materials.

On the other hand, water sorption is significantly influenced by the state of the food materials (e.g. amorphous, crystalline). Water, for instance, can be easily absorbed during rehydration by amorphous food materials (Lian, 2001;Bhandari, 2012). The proportion of crystalline and amorphous phase dominates the structural, functional and physical properties as shown in Table 1.

Table 1 can be inserted about here

During drying, the glass transition temperature (Tg) is the critical temperature at which the material changes its nature from being 'glassy' to being ‗rubbery'. Due to the migration of water the plant based foods matrix become stiffer; and eventually differences in the mechanical properties between fibres and matrix is decreased and may render the food material as glassy and brittle.

Slade and Levine (1991) first introduced the concept of glass transition temperature to explain and identify the physico-chemical modifications in food materials during food processing and storage. This theory gives details of the process of shrinkage, collapse, fissuring, and cracking during drying (Karathanos et al., 1993;Karathanos et al., 1996;Krokida et al., 1998a;Cnossen and Siebenmorgen, 2000;Rahman, 2001). However, Rahman (2001) found that the glass transition theory does not hold true interpretation for all products or processes.

Finally, the porous nature of food material has a significant influence on final food structure and quality attributes (Xiong et al., 1992;Saravacos, 2005). Porosity also affects heat and mass transfer process during drying. Pores can be formed due to both intercellular and intracellular voids in dried food as shown in Fig. 4.

Figure 4 can be inserted about here

Effect of heat and mass transfer on food structure

Microstructure of food material is significantly influenced by heat and mass transfer process during drying. Many studies have attempted to explain effects of heat and mass transfer on microstructure in porous and non-porous materials.

Most of the plant based food materials are treated as capillaryï porous materials, and therefore, the transport of water is a more complex phenomena than in non-porous materials (Datta, 2007;Srikiatden and Roberts, 2007). The structure and elements of food tissue provide resistance to water transfer through different pathways. Cellular foods like fruits, vegetables, and meat form complex structures during drying depending on the extent of dehydration. The resistance faced by liquid water in the pores is different from that faced by water inside the cells (Halder et al., 2011).

Cell membrane normally stays intact before food processing. The main source of water in a tissue is the cell. Haldar et al. (2011) found that more than 85-95% of the water present inside of the selected fruits and vegetables tissue is intracellular at 22 ^{o}C. At low temperatures (between 22 and 50 ^{o}C), the cell membranes remain intact and the transport of water out of the tissue involves migration through both the cells and extracellular space. The main pathway, as shown in Fig. 5a, can be described in terms of water moving from inside the cells through the cell membranes and then the cell walls into the intracellular space. This moisture transport takes place due to the gradient of water potential between cells and the intercellular spaces. The migrating moisture meets resistance from the cell membranes, cell walls and the intercellular spaces (Halder et al., 2011). In the same way, the changing structure of the food tissue significantly affects the rate of moisture migration from the food materials (Fanta et al., 2014).

Figure 5 can be inserted about here

On the other hand, the cell membrane is broken drastically while food is processed at high temperature. At the initial phase, however, drying does not cause any damage to the cells and therefore overall shapes is kept intact (Oikonomopoulou and Krokida, 2013). As drying progress, cell membranes rupture and water is released into the extracellular space (Fig.5b) and therefore the transport of water to the outside occurs predominantly through the extracellular space.

Mass transfer is also affected by shape, size and orientation of the sample. For instance, Carolina et al.(2011) identified that structural arrangements of *Agave* discs had an influence on the rate of moisture loss during drying. They found that discs cut transversely had lower drying rates than longitudinal one. In addition, moisture diffusivity is also influenced by the porosity level of the materials.

All the internal moisture transfer mechanisms are directly or indirectly affected by various food microstructures. On the other hand, different types of moisture transfer mechanism cause various type of microstructure changes in the food product (Joardder et al., 2013d). The moisture transfer mechanisms reported in the literature has been extensively reviewed and summarized in Table 2.

Table 2 can be inserted about here

It can be seen from Table 2 that more than one mass transfer mechanisms can be involved in the drying process. Therefore, difficulty arises where several mechanisms can account for moisture transfer as drying proceeds, though only one of the mechanisms dominates moisture transfer at any given time (Karel and Lund, 2003). In summary, it is quite difficult to anticipate the structure modification due to internal mass transfer mechanism as water of flow pattern at different stage of drying, is not known yet.

Effect of different drying process on microstructure

Drying conditions and methods directly influence physicochemical properties including microstructure, porosity and shrinkage (Rajchert and Rzace, 2009). Most food processes involve heat and mass transfer in a multiphase system and take place simultaneously with physical, macrostructural and macrostructural modifications (Nieto et al., 2004;Karim and Hawlader, 2005b). Apart from the original structural elements in the raw material, dried food properties and structure eventually dependent on type of drying and the processing parameters (Troncoso and Pedreschi, 2007;Huang et al., 2011;Laurienzo et al., 2013). For example, drying of same materials in different methods provides different porosity as shown in the Fig. 6 (Yang and Atallah, 1985;Krokida et al., 1997;Krokida et al., 1998b;Rajchert and Rzace, 2009).

Figure 6 can be inserted about here

From Fig. 6, it is clear that same food material has different range of porosity due to the variation of drying process. It is therefore very essential to choose the right drying method and condition to ensure expected porosity of the final product. For the same reason the microstructure of the finished product differs significantly which is shown in Fig. 7 (Rajchert and Rzace, 2009)

Figure 7 can be inserted about here

Apart from process parameters, coating and blanching influence the microstructure of food materials. The effect of different drying process on food microstructure is described in the following subsections.

Freeze drying

Freezing of food represents a consolidated preservation technology (Delgado and Sun, 2001). As consequence of freeze drying, pure water is converted to ice crystals within the solid matrix of the food stuff. In most of the times it modifies the structure as the volume increases because of lower density of ice compared to liquid water. Crystal growth and nucleation conditions significantly influence properties of foods.

The interaction between kinetic constraints on the formation of crystal and thermodynamic driving forces is generally responsible for the pattern of microstructure in freeze dried foods (Aguilera and Lillford, 2008). On the other hand, this crystal growth and conditions of nucleation strongly depend on freezing time, temperature, freezing rate, water contents of the materials (Voda et al., 2012). Size of crystal is the main property of frozen materials, which depends on freezing rate (Roos, 2012). Under fast cooling condition at lower temperature, ice crystal growth is lower and the pores formed are smaller. Whereas, during slow freezing at higher temperature, more pronounced damaged can be observed because of bigger ice crystal growth, as shown in Fig. 8 .

Figure 8 can be inserted about here

During freezing, growth of an ice compresses, pushes and ruptures the cells and therefore causes cell damage in the form of expansion and shrinkage. However, at intermediate freeze drying temperature (-80^0 C), apple sample was found at quite similar cellular structure of fresh apple structure (Chassagne-Berces et al., 2009). In order to minimize this damage, other assisted method such as radiofrequency along with freeze drying proved better cellular structure retention (Anese et al., 2012).

Amongst the different types of drying , freeze drying provides almost fresh like properties of the food products due to minimal structural damage (Khalloufi and Ratti, 2003). However, from the above discussion, it is clear that to keep the better structure of the freeze dried product, freeze drying temperature and rate should be at intermediate level.

Osmotic dehydration

Many features of cell structure are affected throughout osmotic dehydration of fruits, such as modification of cell walls, splitting of the middle lamella, lysis of membranes, tissue shrinkage, etc. (Alvarez et al., 1995;Alzamora et al., 2000). These tissue changes, which strongly alter the cellular compartmentalization, wall matrix and membrane permeability, could greatly manipulate the transport properties of the product. Thus, the observation of the structural alterations in food tissues allows a better comprehension of mass transfer mechanisms. Nieto el al. (2004) found that the microstructural modifications of apple tissue takes place in the course of the immersion in 25.0% (w/w) glucose aqueous solution as shown in Fig. 9 .

Figure 9 can be inserted about here

Tissues of fresh sample showed noticeable intercellular spaces (Fig. 9a). In some areas, a well-defined middle lamella between cells was also observed. Cells were more or less regular in shape, isodiametric, in general arranged in a loose pattern and attached along extended contact areas. Samples treated for 25 minutes shows a general collapse of the tissues and folding of cell walls can be observed in Fig. 9b. At 125 minutes immersion, the cells seemed to partially recover their shape (Fig. 9c). Finally, at 200 minutes treatment, they obtained tissue arrangement to be more similar to the original one. Cells looked turgid, even more rounded than in the original, and an increase in the size of intercellular spaces occurred (Fig. 9d). From these findings, it is apparent that a proper time of osmotic drying is essential to retain the fresh like structure of the food.

Hot air drying

In hot air drying of fruits and vegetables, in general, tissue is fractured by an extensive shrinkage and microstructural changes (Bolin and Huxsoll, 1987;Aguilera and Chiralt, 2003). Drying parameters serve an active role in determining the textural properties of dried fruits. Slow drying, obtained by low temperature, low air velocity and high air relative humidity, leads to consistent and dense products (Brennan, 1994). In contrast, fast drying rates produces less dense but tougher products, with a crust on the surface (Potter and Hotchkiss, 1998). Vega-Galvez et. al (2012) examined the structural changes of fresh and dried apple at different temperatures as shown in Fig. 10.

Figure 10 can be inserted about here

The tissue of raw apple, as shown in Fig. 10a, provided a clear cell breakage zone; indicating loss of turgor and cell content. This probable turgor pressuree loss presents degradation and causes a possible shrinkage in the contours of the cell wall. Cell damage is least at 40^0C (Fig.

10b) while at higher temperature (80^0C) thermal destruction predominates and weakened the cell tissue (Fig. 10c and d).

The drying temperature and drying rate are the most important factors that influence the microstructure of dried samples (Rajchert and Rzace, 2009). At low temperature, as the diffusion rate of internal moisture to surface of foods is almost equal to evaporation from the surface, no discernible moisture gradient is found within the food sample. Consequently, cell collapse takes place within the food material only in the final stage of the drying. On the other hand, moistutre evaporation rate is very high at higher temperatures, which causes stiff surface. Therefore, product with higher porous structure is developed in case of high temperature air drying.

However, as reported in the literature, intermediate air temperature causes less cell damage with moderate moisture removal rate. An investigation by Russo et al. (Stevenson et al., 1996) found better preserved structure at intermediate temperature (60^0C) compared with other dehydrated samples at temperature of 40, 50 and 70 °C. Specially, at 70 °C the structure of dried samples were totally broken due to faster moisture transfer rate. Therefore, an intermediate temperature approximately 60^0C is considered suitable for better retention of structural properties of finished product during hot air drying.

Microwave drying

In order to overcome shortcomings of convective drying, microwave assisted convective (MWC) drying process was developed. Therdthai and Zhou (2009) found that to hot air drying, microwave vacuum drying can lessen the drying time of mint leaves by 85ï 90%. Since the least efficient part of the conventional drying is the final stage of drying, use of microwave energy at that stage will help to remove the last one-third of the moisture content (Maskan, 2001). It can be assumed that using microwave energy in the initial stage of drying leads to cellular collapse and bulk shrinkage in the final products. Therefore, the microwave stage can be used in the last stage of the dehydration process (i.e. during the falling rate period).

In addition of this, puffed structure can be manipulated by controlling microwave power and pressure (Lin et al., 1998). Microwave heating disrupts cell walls (Funebo et al., 2000).Therefore, very tiny (nano level) pores on cell wall can be found as shown in Fig. 11 (Joardder et al., 2013b). This can be linked with the migration of relatively loose bounded water occurred with higher temperature.

Figure 11 can be inserted about here

During microwave drying, food structure is mainly dominated by microwave power (Joardder et al., 2013c). At low microwave power, the cell structure is found intact due to weak induced force (Khraisheh et al., 2004).Whereas, higher microwave power leads higher drying rate which causes breakage of the cell wall.

Given these points, low power microwave application at the last stage of combined drying is more effective in terms of finished product quality.

Combined drying and other novel drying methods

In order to achieve superior quality of dried food, different combined drying techniques and other novel drying processes have been applied in the field of drying technology. However, in most of the cases the process was developed for particular types of food materials. Performance and impact of these types of drying method on dried food microstructure are summarised in Table 3.

Table 3 can be inserted about here

Structure- properties relationships

The structure of food stuff influences their physical, sensorial and transport properties and bioavailability of nutrients (Aguilera, 2006). Changes of many physical attributes are eventually due to alternation of the product microstructure (Ramos et al., 2004;Panyawong and Devahastin, 2007;Witrowa-Rajchert and and Rzaca, 2009). Since the understanding of the correlations between physical and microstructural changes could help design and identify an optimum drying conditions, many studies have been conducted to investigate such relationship of various food product (Achanta and Martin, 1996;Riva et al., 2005;Askari et al., 2009;Yang, 2010;Ghosh and Dimiduk, 2011;Gumeta-Chavez et al., 2011).

These studies reported remarkable evidence that the initial microstructure characteristics of a sample influence the final quality after drying (Therdthai and Visalrakkij, 2012;Giri and Prasad, 2007). In other words, finished productôs microstructure to some extent depends on the original microstructure of the raw food material (Aguilera and Chiralt, 2003). In the following sections, studies on structure- properties relationships are discussed.

Sensory quality

In order to produce desired quality processed food, understanding of the relationship between sensory quality and microstructure is essential (Langton et al., 1997). In general, flavour perception in mouth decreases with the increase of the viscosity (Baines and Morris, 1987). Higher pores with larger exposed surface area allows intense taste to mouth during mastication (Wilson and Brown, 1997). In other word, more surface area in contact with tongue or other sensory organ provide intense taste of the product. Food matrix components, such as proteins, polysaccharides, and lipids are known to interact with favour compounds (Bakker and Mela, 1996).

Food physiochemical properties and the structure of food matrix can modify the thermodynamics and kinetics of flavour release (De Roos, 2003;Mezzenga et al., 2005;Laurienzo et al., 2013). Several studies were conducted concerning the significance of the solid matrix on releasing of flavour and aroma and significant relationship between these have been found (Cayot et al., 2004;Boland et al., 2006;Seuvre et al., 2006;Lafarge et al., 2008).

Empirical models were developed to establish relationship between the sensory quality and microstructure, one of these types of equations is shown below (Langton et al., 1997):

$$Y = A + B\log(X)$$

Where, Y is a sensory descriptor, X is a microstructural parameter, and A and B are correlating constant.

From the previous studies on the relationship between microstructure and sensory properties, an important hypothesis was derived by Kalab (1995) that the foods having a similar microstructure also have a similar sensorial behaviour .

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Texture

Microstructural changes during drying must be taken into consideration as these changes lead to changes in the textural characteristics of dried fruits and vegetables (Reeve, 1970;Rahman, 2008). Although there is limited literature that dealt with the structure-texture relationship, evidence is found about associations between moisture release rate, hardness and brittleness (Varela et al., 2007). Existing modeling of the relationship between texture and microstructure has been review by Chen and Opara (2013). It is found that not only food structure and its surface properties but also rheology influence food texture (Kravchuk et al., 2012;Stokes, 2013). Different other mechanical properties of several foods have been found closely related to their structure (Oikonomopoulou and Krokida, 2012).

Heath and Lucas (1987) state that texture perception would depend on three main disciplinary approaches namely; sensory, physiology and food structure as shown in Fig.12.

Figure 12 can be inserted about here

From the Fig. 12 it can be seen that food structure directly influences the physiological interaction during oral process; subsequently the oral perception detects the texture of food materials. However, the relationship between food structure and texture anticipation is not straightforward due to the dynamic feature of texture perception and presence of diversification of processes (Wilkinson et al., 2000).Therefore, more research is required in order to establish more rational relationship between texture and microstructure of food.

Nutrient bioaccessibility/bioavailability

Bioavailability of nutrient is considered more important nutritional feature than the amount of nutrition content in both raw and processed foods. The rate of nutrient delivery evidently depends on food structure as structure controls diffusion of nutritional molecules (Sharma, 2012). For example, it is found that ascorbic acid loss is higher for larger exposed surface area (Santos and Silva, 2008). Several factors including food structure, process conditions and environmental conditions influence the bio-accessibility of food nutrients (Parada and Aguilera, 2007). For example, it is found that bioavailability of lipids may be decreased or increased due to manipulation of the food microstructure that contain them (Decker et al., 2008). A recent review compiled the effects of food structure and processing on bioavailability and bioaccessibility of functional components (Sensoy 2014) .

Food microstructure plays an important role in absorption and release of the nutrients components (Norton et al., 2007). Complex structure of foods may resist the bioaccessibility of nutrients as most of the nutrients remain either inside the cells or connected to the cellular matrix (Sensoy 2014). In addition, Parada and Aguilera (2007) came up with a postulation that disruption of natural matrix or microstructure created during processing may influence the release, alteration, and succeeding absorption of some nutrients in the digestive tract.

Cell walls of particular plant foods sometimes become a cause of resistance to the release of nutrients for digestion. Components of foods such as starch also influence the release of other nutrients from food materials.

During any types of processing the bioaccesibility may be altered significantly. Clearly then, drying can moderate (either decrease or increase) the bio-accessibility and rate of digestion.

However, little is known about the amount of food nutrients that migrates from food material during drying. In addition, there is inadequate studies concerning the optimum drying condition in order to achieve maximum retention of nutrients.

Electromagnetic Properties

Food materials hold polar molecules that react to microwave radiation. Once foods are placed into a microwave field in which microwaves are released at special frequencies, polar molecules can become electrically polarized, and can absorb microwave energy (McKenna et al., 2006). As porous dry food material possesses pockets of air, they show poor absorption of microwave energy (Khraisheh et al., 1997;Adapa et al., 2002).

At present, very little is known about the dielectric properties of moist materials of different structures containing water at various levels of binding. Dielectric properties are the most important physical properties associated with radio frequency (RF) and MW heating, since the dielectric behaviour affects their heating characteristics of foods (Sosa-Morales et al., 2010). The dielectric properties depend on the temperature of the material, density, composition, and structure of the material (Venkatesh and Raghavan, 2004). It is established that the more porous the material become during drying, the more entrapped air present in it; consequently, it shows lower dielectric properties (Feng et al., 2012).

Colour

During drying, colour can be significantly affected by tissue enzymatic activity (Hansmann and Joubert, 1998) and pigment degradation (Grabowski et al., 2002;Reyes et al., 2002). However, modifications of light reflectance ability of food surface due to evolution of porosity and changes of surface texture must also be taken into consideration (Fornal, 1998;Lewicki and Duszczyk, 1998;Lewicki and Pawlak 2003). Appearance of food materials depends on several factors including the ability of food to scatter, transmit, reflect or absorb visible light as shown in the Table 4 (Wyszecki and Stiles, 2000). All these capabilities are directly related to structure of exposed surface. Due to simultaneous heat and mass transfer from the material during drying process, both internal and external surfaces of food material change.

Table 4 can be inserted about here

Light intensity is considerably affected by the change of moisture content and structure alternation. Altered tissue structure in the course of drying may have caused dispersion photons on the surface resulting in changing the degree of scattering (Romano et al., 2012). In addition, shadow developed due to collapsed structure also causes reduction of light intensity.

Figure 13 can be inserted about here

In visual observation, generally a darker surface in the sample is perceptible with the progression of drying due to water reduction and cell collapse. In Fig. 13, obtained from image analysis using image pro premier, there is a clear trend of decreasing light intensity with decreasing moisture from food materials (Joardder et al., 2013b).

Moreover, the prime cause of colour change during drying is the browning reaction due to simultaneous heat and mass transfer (Fu et al., 2007). Loss of cellular turgor pressure leads to microstructural changes. Subsequently, it may increase the effective release of different chemical reacting agents; accelerating Maillard reaction which causes higher browning rates (Acevedo et al., 2008).

In essence, both optical and browning characteristics determine colour, which depends on food structure. In light of findings, better appearance of the product can be ensured by controlling the structure of the food product.

Shrinkage

In general, shrinkage depends on the types of solid matrix and the composition of plant origin as well as drying conditions (Sjöholm and Gekas, 1995;Prothon et al., 2003;Kerdpiboon et al., 2007). For example, because of the more fibrous structure of pineapple, which implies that its structure is already confined from collapse by this fibrosity, eventually less shrinkage takes place during osmotic drying (Botha et al., 2012). During drying, microstructural stress is induced due to moisture gradients within the product leading to shrinkage of the product. Shrinkage may take place because of two causes. Firstly, the tissue is incapable to hold its structural arrangement when the space occupied by water is constantly emptied and air-filled. Secondly, the exterior skin structure collapse leads to shrinkage (Panyawong and Devahastin, 2007). Consequently, the internal structure of the food material is deformed and locally collapsed (Lewicki and Pawlak, 2003). Shrinkage influences the quality of the product by declining its wettability, altering its texture and reducing the capacity of adsorption (Genskow, 1998). On the other hand, pore formation is just opposite to the shrinkage of food material during drying. In addition, uniform pore formation opposes destructive phenomenon of shrinkage and consequently rehydration property significantly increases. Porous foods tend to shrink less than non-porous foods during drying due to the fact that porous foods normally have less initial moisture content than non-porous foods (Srikiatden and Roberts, 2007).

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During drying or other heating mechanisms, porosity of most food materials are changed, which in turn significantly influence heat and mass transfer (Joardder et al., 2013e). However, some of the food materials develop insignificant amount of pore during and after food processing. Such occurrence is observed in case of drying of carrots and potatoes that build up almost negligible porosity (<10%). On the other hand, apples develop considerable porosity (0.20 to 0.70) (Lozano et al., 1983;Zogzas et al., 1994). Current study confirms that not only materials characteristics but also drying process parameters influence the porosity (Joardder et al., 2013b).

Rehydration

Rehydration characteristic is related to the textural feature of food products. In other words, higher rehydration rate manifests to more interconnected porous structure. In contrary of this, high shrinkage and low porosity lead to products with poor rehydration capabilities (Mcminn and Magee, 1976;Mayor and Sereno, 2004). It is caused due to the irreversible collapse phenomenon following the loss of turgidity during drying. In addition to this, the shrinkage phenomenon that takes place during dehydration prevents rehydration. Freeze dried materials seem to have higher and quicker rehydration ability, while air and microwave dried products show the lower (Laurienzo et al., 2013;Oikonomopoulou and Krokida, 2013;Pei et al., 2014). It may be due to the closed or blind pores development in food sample during hot air drying and microwave, whereas freeze drying causes less cellular shrinkage and develop many open pores.

The major hindrance to the invasion of the pores by the rehydrating fluid is the existence of air bubbles. Pore structure and presence of air bubble in pores resists the absorption of rehydrating water. In case of cell wall rehydration, the component and nano-porous nature of cell wall ensure rehydrated water in bound state. However, crystalline state of cell wall does not allow water uptake and offers obstacle to rehydration phenomenon (Prothon et al., 2003).

Thermal properties

Similar to mass flow, heat transfer also depends on food compositions and its structure matrix. Food materials possess low thermal conductivity and therefore heat transfer rate is critical in product quality (Fryer, 2012). In porous solids such as foods, thermal conductivity depends mostly on composition but also on many other factors that affect the heat flow paths through the material, such as void fraction, shape, size and arrangement of void spaces, the fluid contained in the pores, and homogeneity (Sweat, 1995). Thermal conductivity in foods having fibrous structures is different in different directions (anisotropy) as heat flow paths through the material change with respect to direction.

Thermal conductivities of food materials vary between that of water (k_{water} = 0.614 W/m^{0}C C at 27 ◦C) and that of air (kair = 0.026 W/m^{0}C C at 27^{0}C C), which are the most and the least conductive components in foods. The thermal conductivity values of other food components fall between these limits. Dry porous solids are very poor heat conductors because the pores are occupied by air.

Factors that affect the thermal conductivity of foods include: process conditions, food composition and structure (Datta et al., 2007). Water content plays a significant role in thermal conductivity of food. The non-aqueous part of food such as fats and oils also play an important role in thermal conductivity in fatty foods. The structural factors that influence thermal conductivity include porosity, pore size, shape and distribution, arrangement or distribution of different phases, such as air, water, ice, and solids. Several attempts have been made to correlate conductivity as a function of food microstructure and composition (Becker and Fricke, 1999;Fikiin and Fikiin, 1999;Carson et al., 2005;van der Sman, 2008).

CONCLUSION

Proper knowledge of structural changes during drying is essential in order to develop more rational and energy efficient food drying. Retaining the structure of the fresh foods and structural functionality are utmost importance for the food industries. Despite many research works that have been conducted in this area, relationship between food microstructure, heat and mass transfer within foods during drying, and food quality still remains unclear to the researchers. Mass transfer in food materials involves many different internal moisture transfer mechanisms which noticeably depend on the composition, properties, and structure of the initial food, the drying process conditions.

To date, there have been limited investigations concerning the relationship between food structure and food quality, and selection of optimum drying parameters. However, it emerges from this study that understanding of the physicochemical behavior of food material is very important in order to design optimum of food processing for maximizing quality of processed food.

After reviewing the current literature in food microstructure research, this paper conclude that it is possible to relate structure, process parameters and food quality during or after drying process. If the relationship can be established, it is possible to design a drying process that can ensure microstructural pattern of finished product closer to fresh food structure. In addition, heat and mass transfer phenomenon must be properly understood for better nutritional retention. Finally, developing the relationship between process parameters, microstructure and food quality requires multidisciplinary contribution.

Therefore, researchers and scientists from different fields can incorporate their knowledge and endeavour in order to establish a bridging relationship between process conditions, food structure and product quality. This key relationship would assist in developing a cost effective and better quality food processing system.

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Table 1.Differences in physical properties between crystalline and amorphous states of materials (Bhandari, 2012)

Properties	Crystalline state	Amorphous state
Density	High	Low
Mechanical strength	Strong (Ductile)	Brittle
Compressibility	Poor	Good
Internal porosity	Low	High
Hygroscopicity	Low	High
Softening temperature	High (Melting)	Low (glass transition)
Chemical reactivity	Low	High
Interaction with solvent	Slow	Rapid
Heat of solution	Endothermic	Exothermic

Table 2. Internal moisture transfer mechanism during drying of solid foods

Reference	Moisture transfer mechanism during drying	
Lewis (1921), Sherwood (1929a) , Sherwood (1929b)	Diffusion	
Ceaglske and Hougen (1937)	Capillary	
Henry (1948)	Evaporation-condensation	
Görling (1958)	Transfer of liquid water Capillary Liquid diffusion Surface diffusion	Transfer of water vapor Differences in partial pressure (diffusion) Differences in total pressure (hydraulic flow)
Van Arsdel (1963)	Capillary Diffusion Surface diffusion in liquid layers absorbed at solid interfaces Water vapour diffusion in air filled pores Gravity Vaporization-condensation sequence.	
(Keey, 1970)	Hydraulic flow Capillary flow	

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	Evaporation-condensation Vapor diffusion	
Bruin and Luyben (1990)	Molecular diffusion Capillary flow Knudsen flow Hydrodynamic flow Surface diffusion	
Hallstöm (1990)	Transfer of liquid water Capillary (saturated) Molecular diffusion (within solid) Surface diffusion (absorbed water) Liquid diffusion (in pores) Hydraulic flow (in pores)	Transfer of water vapor Diffusion (in pores): - Knudsen, - Ordinary, -Stephan diffusion. Hydraulic flow (in pores) Evaporation-condensation
Waananen et al.(1993)	Transfer of liquid water Capillary diffusion Surface diffusion Hydraulic flow	Transfer of water vapor Mutual diffusion Knudsen flow Diffusion Slip flow Hydrodynamic (bulk) flow Stephan diffusion

Poiseuille flow

Evaporation-condensation

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Table 3. Effect of different combined and novel drying processes on dried food microstructure

Principle drying	Assistant drying	Comparative chage in microstructure	Food materials	Ref.
Freeze drying (FD)	Microwave drying	Less regular and uniform pore size and pore distribution than FD	Stem lettuce	(Wang et al., 2012)
	Microwave vacuum drying (MWVD)	Less collapse than in MWVD+FD	Apple	(Huang et al., 2012)
	Pulse-spouted freezing and microwave	More uniform pore size and compact microstructure compared to microwave FD.	Stem lettuce	(Wang et al., 2012)
	Hot air drying	Suffered severe collapse	Button mushroom	(Pei et al., 2014)
	Vacuum drying	Larger pore structure		
	Radiofrequency	Better cellular strycture preserved than freeze drying	Meat	(Anese et al., 2012)
Hot air	Ultrasonic	Less collapse or less compact	Eggplant,	(Puig et al.,

drying (HAD)	drying	cell than HAD . better raw structurepreservation	apple	2012;Sabarez , 2012)
	Saturated stream drying	Contains enormous small voids	Longon	(Somjai et al., 2009)
	Intermittent microwave	Better microstructure than continuous microwave assisted drying	Fruits	(Kumar et al., 2014)
Osmotic drying (OD)	Fluidized bed drying	More porous than OD	Bamboo Sooth	(Badwaik et al., 2013)
	Ultrasound	A lot of microscopic channels appeared in the cell structure	Pineapple	(Fernandes et al., 2009)
Microwave drying	Vacuum drying	Higher porosity and less shrinkage than HAD	Carrot	(Lin et al., 1998)
Heat pump	Freeze drying	Significantly lower collapse than freeze drying	Various fruits	(Uddin et al., 2004)
Superheatd ï steam drying	Hot air drying	Most of the pores are small except few large cavities . Sturcture is found	Longan	(Somjai et al., 2009)

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	homogonous.		
Novel drying methods			
Supercritical carbon dioxide drying	Better retention of original structure along with more porous structure than HAD	Carrot	(Brown et al., 2008)
Dehydration by biofilm	Retention of largely undamaged cells	Apple	(Laurienzo et al., 2013)
Pressure drop Drying	Highly porous with different size of porosity	Apple	(Mounir et al., 2011)
Electro hydrodynamic drying	Comparatively less collapse in cell	Apple	(Alemrajabi et al., 2011)

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Table 4. Factors influencing the colour of a material (Wyszecki and Stiles, 2000)

Factors	Structural factors
Illumination	Type of light, illumination angle
Transmission	Material, particle size
Absorption	
Emission	Surface properties, absorptivity
Reflection	
Observation	Observer, observation angle

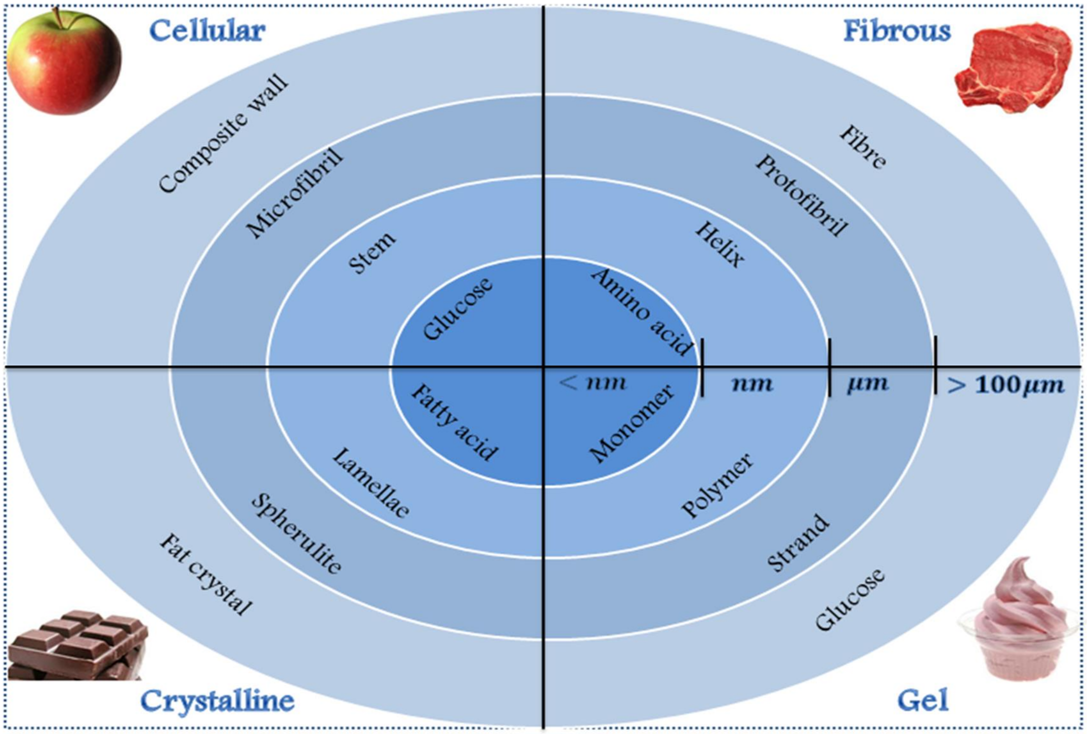

Figure 1. Demostartion of the hierarchical structure of different food materials

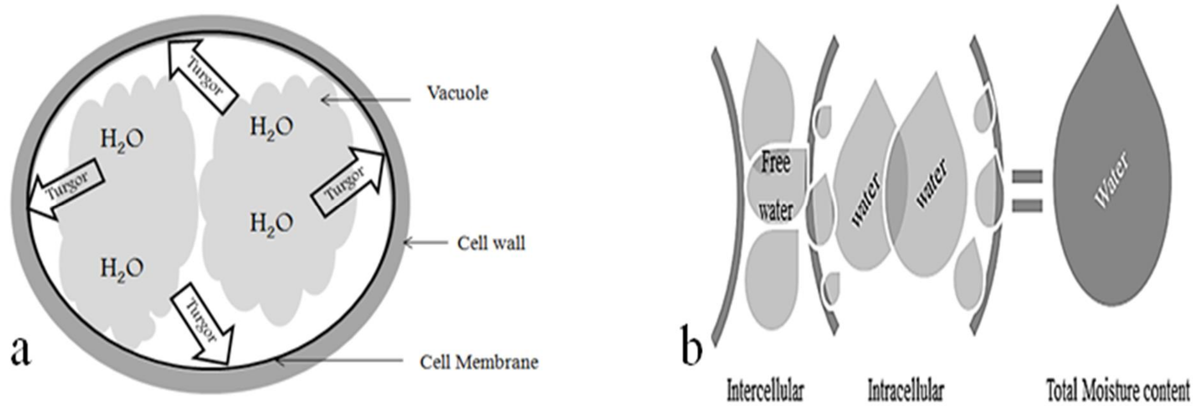

Figure 2. (a) Turgor pressure in parenchyma cell and (b)water distribution within plant tissue

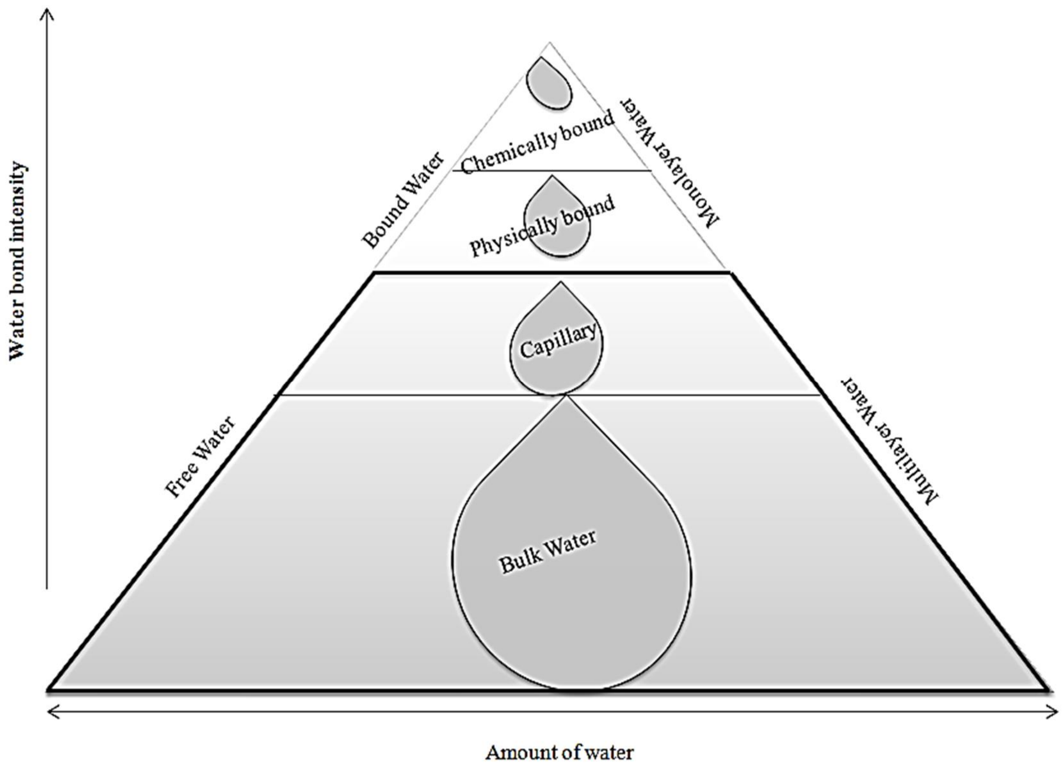

Figure 3.Proportion of different types of water in food materials

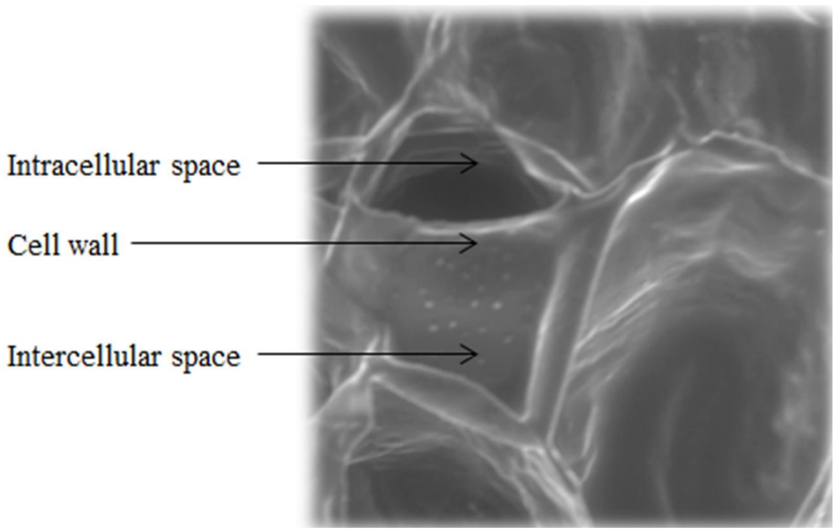

Figure 4.Microstructure of apple tissue showing intracellular and intercellular spaces

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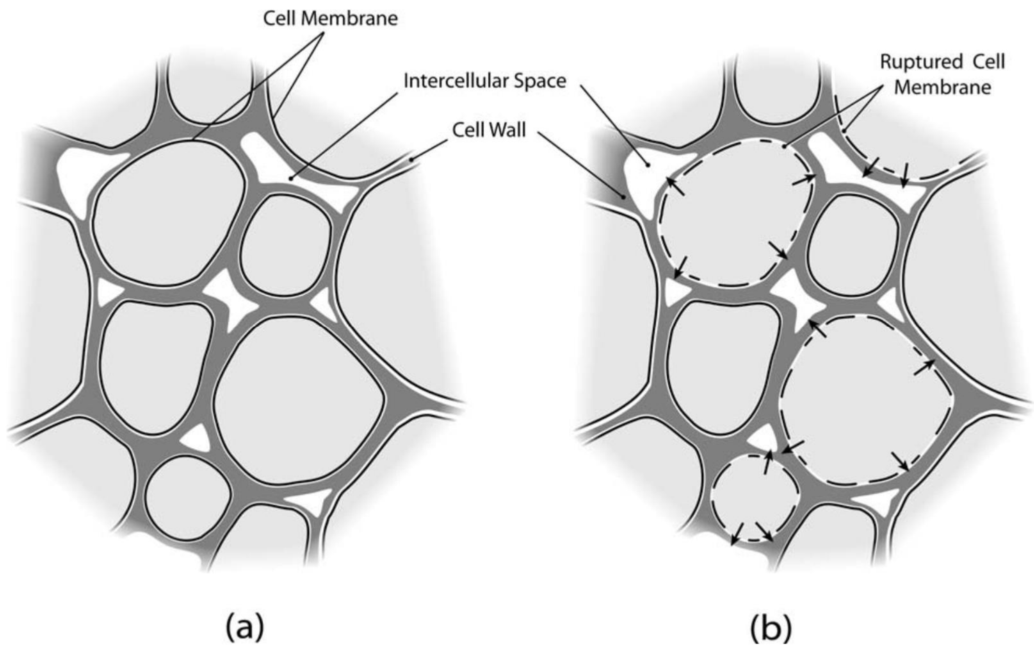

Figure 5.Schematic showing the cell membrane structure at (a) temperatures below 52 ^{o}C (low temperatures); (b) temperatures above 52 ^{o}C (high temperatures). Adapted from(Datta, 2007)

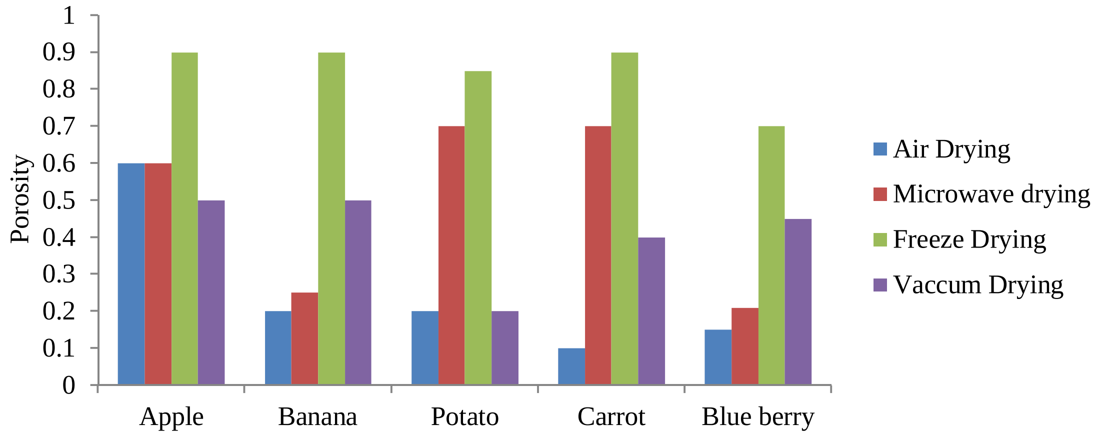

Figure 6.Variation of porosity in different food in different drying condition

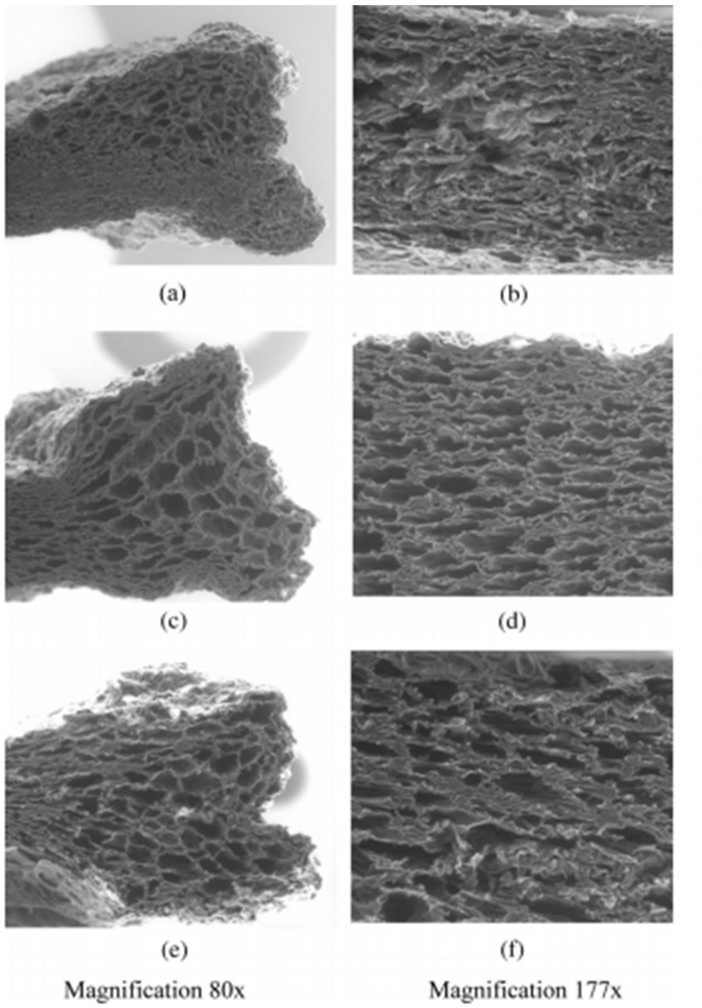

Figure 7. Micrographs of shore and middle of dried apples (a,b) convective dried; (c,d) microwave convective dried; (e,f) infrareddried apples. Adapted from (Rajchert and Rzace, 2009)

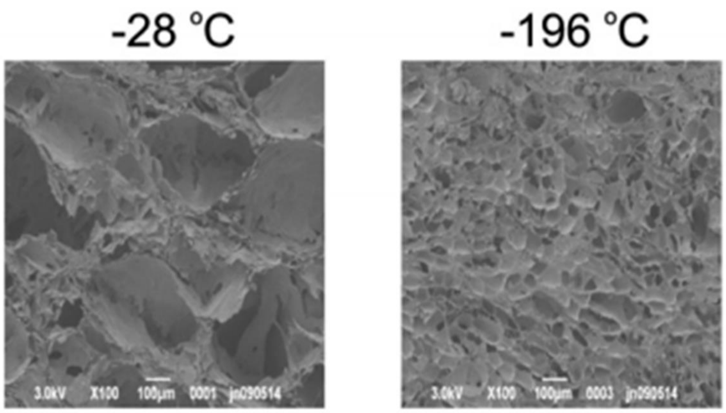

Figure 8. SEM images of carrot tissue freeze- dried at -28 and -196 ^{o}C. Adapted from (Voda et al., 2012)

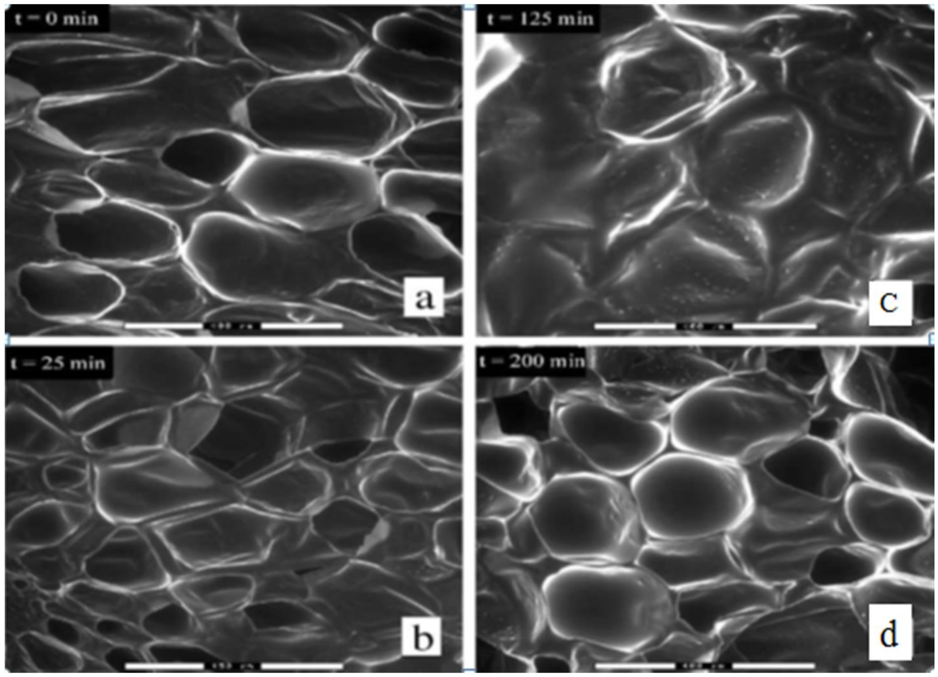

Figure 9. ESEMs of parenchyma tissue of apple at different impregnation stages in 25.0% w/w glucose aqueous solution at 30 ^{0}C: (a) fresh control; (b) after 25 min; (c) after 125 min; (d) after 200 minutes. Adapted from (Nieto et al., 2004)

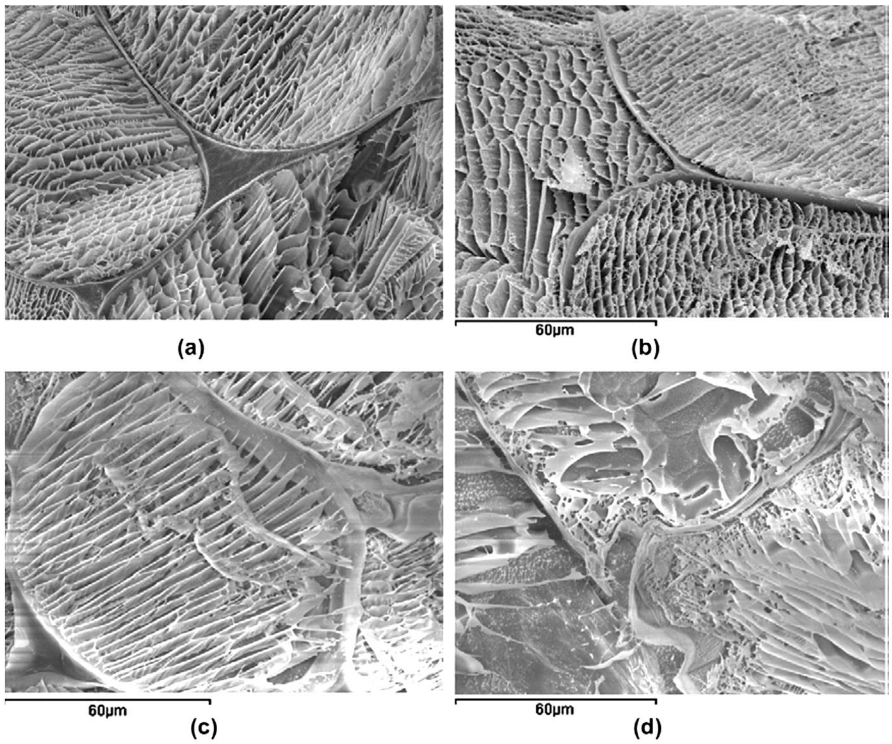

Figure 10. Structural change during hot air drying: a) raw apple, b) at 40^0 C, c) 70 ^{0} C & d) at 80^0 C. Adapted from (Vega-Gálvez et al., 2012)

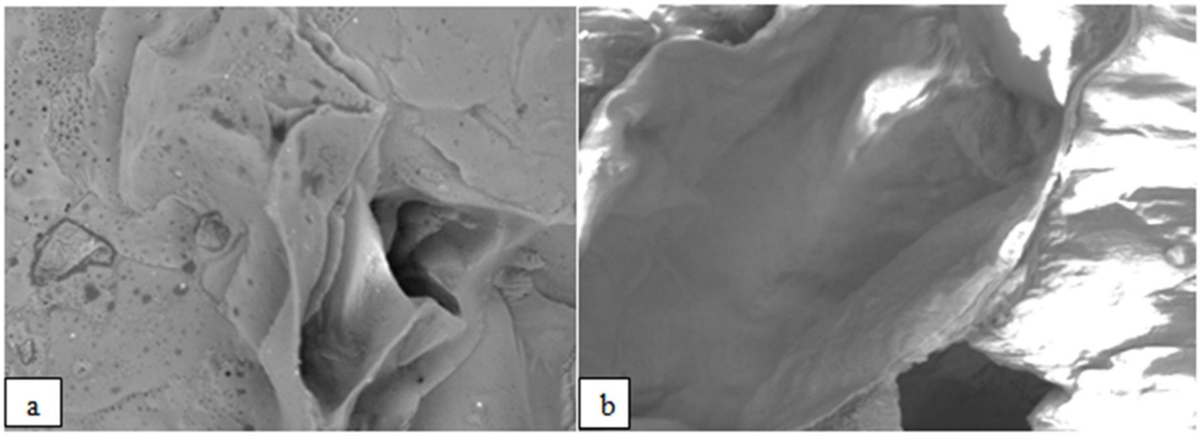

Figure 11. Existence of tiny pores in microwave dried food (a) comparing with convective dried food (b)(Joardder et al., 2013b).

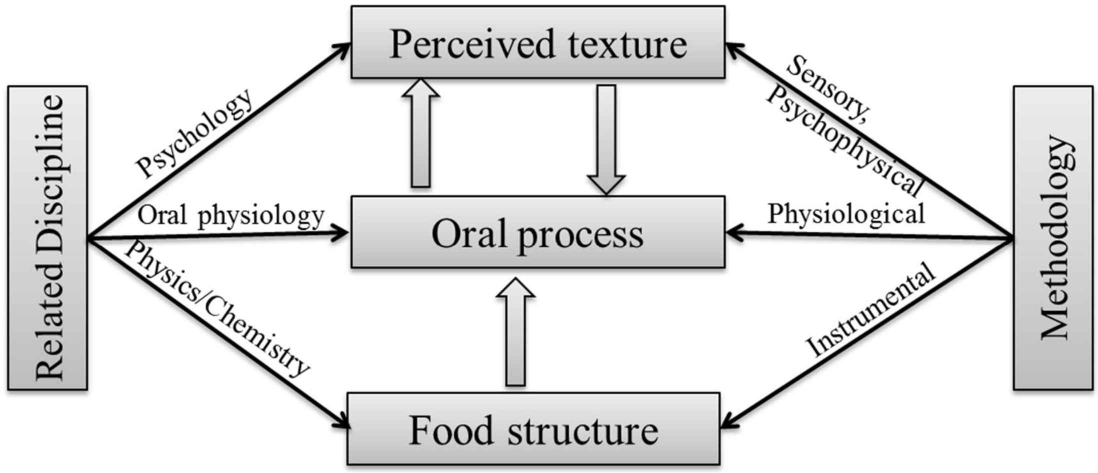

Figure 12. Interrelationship between food structure and texture.

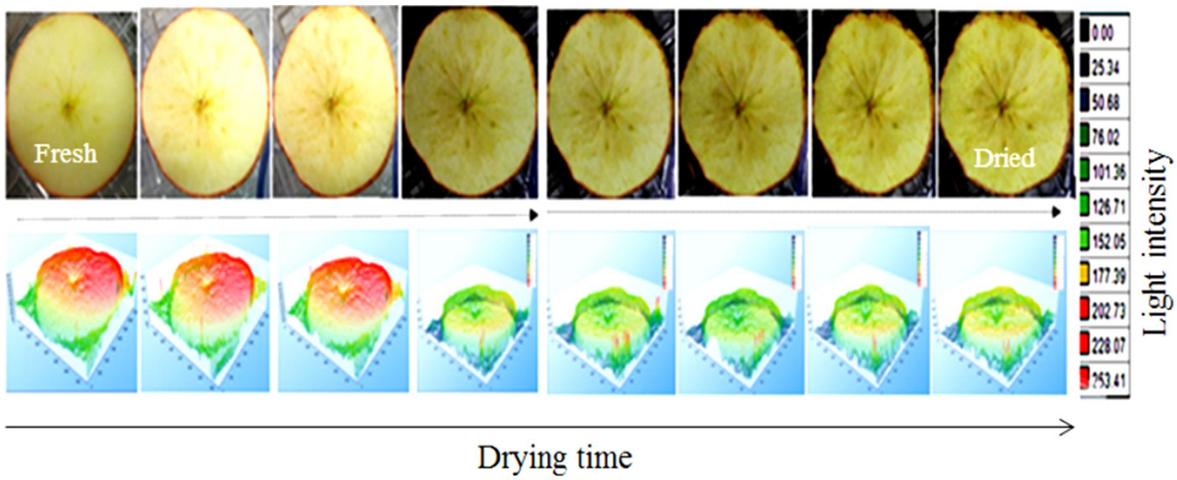

Figure 13. Change of image intensity with proceeds of convective drying of apple slice at 70 ^{0}C (Joardder et al., 2013b)