STRUCTURAL CHANGES DURING AIR DRYING OF FRUITS AND VEGETABLES: *A REVIEW*

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INTRODUCTION

Drying a solid is usually regarded as the removal of water or other liquid from the solid material till an acceptable low value (McCabe *et al.*, 1993). Many authors use "drying" to describe the natural process of water removal by exposure to the sun (Brennan, 1994) and "dehydration" as the artificial drying under controlled conditions (Potter and Hotchkiss, 1998).

Drying is probably the oldest method of preserving foods. Ancient civilisations preserved meat, fish, fruits and vegetables using sun-drying techniques (Brennan, 1994). Dried foods were the mainly supply of troops along the centuries and were particularly popular during both World Wars.

Nowadays, drying is regarded not only as a preservation process, but also as a method for increasing added value of foods. Among foodstuffs, particular attention has been given to drying of fruits and vegetables. Diversified products can be obtained to include in breakfast cereals, bakery, confectionery and dairy products, soups, purees and others.

Loss of water and volatiles, which occur during drying, results in major structural changes in materials that lead to textural and sensory characteristics different from the fresh product. These properties are utmost important to be kept, due to the growing consumer's appeal for products with freshly characteristics.

Although being a relatively well-studied process, there is a lack of information concerning structural changes during drying. In the following sections a review of existing studies related to structural changes during drying of fruits and vegetables will be presented. These will include, among others, changes in volume, porosity and density, that directly affect textural attributes and microstructural characteristics of the products.

MICRO AND MACROSTRUCTURAL CHANGES

Drying processes lead to changes of foods at microstructural level, consequently affecting their macroscopic characteristics. Loss of water and segregation of components occurring during drying, result in rigidity of cell walls. Damage and disruption of the cellular walls may happen, and even collapse of the cellular tissue may occur. These changes are associated with volume reduction of the product (Mattea *et al*., 1989).

Frequently, at fast drying processes, the product surface dries much faster than its core, a phenomenon that originates internal stresses and, as a consequence, the product interior gets very cracked and porous (Aguilera and Stanley, 1999). Non-volatile compounds migrate with the diffusing water and precipitate on the product's surface and form a crust that keeps the product dimensions thereafter. Wang and Brennan (1995) observed such phenomena through microscopy with potato drying experiences.

Microstructural studies may improve the understanding of drying mechanisms and the knowledge of food properties. Observing what happens at the microscopic level during drying results not only on qualitative information, but also on quantitative data suitable to modelling. Understanding the relationship between food microstructure and food perceived characteristics is of increasing importance to produce attractive food products (Wilkinson *et al.,* 2000).

Changes in geometric features of cells may be quantified by image analysis (Bolin and Huxsoll, 1987). Nowadays, several microscopes with high magnification and resolution power can be used to study food microstructure (e.g. scanning electron microscopy is widely used). Microscopy, especially if complemented with image analysis, is a powerful non-invasive tool for studying food microstructure (Jewell, 1979). Stereo-microscopy has limited magnification, but due to its large focal distance it allows the observation of large food pieces during drying, unlike other methods in which it is only possible to visualize a small region of transparent sample. The information obtained from the microscope is then suitable for quantification, using software for image analysis (Aguilera and Lillford, 1997).

These techniques are not commonly used in drying studies. Bolin and Huxsoll (1987) applied scanning electron microscopy and image analysis when studying apple drying; Wang and Brennan (1995) used light microscopy for studying structural changes in potato during drying. More recently, Ramos *et al*. (2002) applied stereo-microscopy for quantification of several cellular parameters directly related to dimensions, when studying structural modifications during drying of grapes. These authors developed a kinetic approach to model microstructural changes.

Shrinkage

Loss of water during a drying process originates a reduction in the size of the cellular tissue, which is usually referred as *shrinkage* phenomenon.

Reeve (1943) and Crafts (1944) reported pioneer studies of shrinkage at microscopic level, related to dehydration processes of carrots, potatoes and several fruits.

General empirical shrinkage models have been proposed for fruits and vegetables during drying (Suzuki *et al*., 1976; Vagenas *et al*., 1990; Madamba *et al*., 1993; Zogzas *et al*., 1994). Lozano *et al*. (1980) expressed shrinkage on the basis of the ratio between the bulk volume of the product and the initial bulk volume (bulk shrinkage coefficient).

The shrinkage phenomenon could be very intensive, depending on the drying method applied (Krokida and Maroulis, 1997) and on drying conditions. Shrinkage affects mass and heat transfer parameters, being nowadays recognised as an important change that has to be accounted for, when establishing drying models.

Glass transition theory could be one concept that explains the process of shrinkage and collapse during drying (Rahman, 2001).

PHYSICAL PROPERTIES

The most important physical properties that characterise the quality of dry and intermediate moisture foods are: porosity, bulk density and particle density (Zogzas *et al*., 1994). An obvious relationship exists between the water content and these properties; nevertheless the modelling of drying process frequently does not include those effects. Reported studies are relatively scarce and, for predictive purposes, a standard methodology has not been established yet. Relating physical properties with microstructure is a relative new and attractive area, which also requires a lot of researching effort.

Porosity

Porosity is defined as the ratio between volume of pores and the total volume of the product (Lewis, 1987). A porous foodstuff presents better reconstitution properties (re-hydration rate and capacity), but has a shorter shelf-life due to increased surface exposition (Potter and Hotchkiss, 1998).

During drying, the product porosity increases as the water and volatiles are removed. However, Krokida and Maroulis (1997) concluded that the porosity of the final product could be controlled, if an appropriate drying method is chosen. Air-dried products present low porosity when compared to freeze, microwave and vacuum drying. Porosity is directly dependent on initial water content, composition and volume (Krokida *et al*., 1997).

Lozano *et al.* (1980, 1983) correlated porosity with water content for several fruits and vegetables (apple, pear, carrot, potato, sweet potato and garlic). Zogzas *et al*. (1994) concluded that air-dried carrots and potatoes developed almost negligible porosity when compared with apples. These authors also derived a mathematical model, correlating porosity with water content. A similar approach was carried out by Krokida and Maroulis (1997), including experiments with banana. More recently, Tsami and Katsioti (2000) tested the proposed model with avocado, prune and strawberry.

Besides porosity, pore size and pore size distribution of a food are important structural characteristics. Karathanos *et al*. (1996) performed studies on porous structure, including the determination of these parameters with potato, apples, carrots and cabbage subjected to a drying process.

Lozano *et al*. (1980) divided the porosity of apples between total and open pore porosity. Total porosity includes pores connected to the outside and locked-in or closed pores, and open pore porosity accounts just for externally connected pores.

Density

Particle density

Particle density is defined as the particle mass divided by the particle volume, disregarding the volume of all pores (Lewis, 1987).

It would be expected that, as the food loses water, the value of the particle density ranges between the water density and the dried material density.

Several authors (Lozano *et al*., 1980, 1983; Vagenas *et al*., 1990; Zogzas *et al*., 1994; Karathanos *et al*., 1996; Krokida *et al*., 1997; Krokida and Maroulis, 1997) studied the effect of drying on particle density and correlated this parameter with water content of diversified fruits and vegetables (apple, banana, grapes, pear, carrot, potato and garlic). They observed that as water content decreases the particle density increases. However, for apple and carrot, Lozano *et al*. (1980, 1983) detected a peculiar behaviour consisting on an inverted tendency for lower values of water content. In those situations, after a critical low water content value is reached, the particle density shows a sharp decrease, as water content tends to zero. According to these authors, in the last drying stages there is an increasing number of pores which become closed, therefore they cannot be accounted in volume measurement.

Bulk density

Bulk density (sometimes called apparent density) is defined as the particle mass divided by the particle volume, including the volume of all pores. During drying and as food loses water, the bulk density increases (the value of bulk density varies between the density of pure water approximately and the bulk density of dry solid).

This tendency was observed by several authors (Lozano *et al*., 1983; Zogzas *et al*., 1994; Madamba *et al*., 1994, Krokida *et al*., 1997; Krokida and Maroulis, 1997) dealing with drying of carrot, pear, banana, potato, sweet potato and garlic. In some cases, in similarity with what was found for particle density, at low water content values a pronounced decrease of bulk density was detected. Zogzas *et al*. (1994), explained this behaviour through the development of product porosity along the drying process.

Karathanos *et al*. (1996) observed an almost constant bulk density of carrots, not varying with water content.

TEXTURE

Texture is a difficult property to define. It can be considered an external reflection of micro and macrostructural characteristics of a food product (Aguilera and Stanley, 1999) that directly influences its sensory perceived features. The perception of texture is a synthesis of information from several senses, a complex process involving sensory research, physiology studies and research into food physicochemical characteristics (Wilkinson *et al*., 2000).

Texture of fruits and vegetables is affected by drying processes, and it is strongly associated with composition and structure of cell walls (Reeve, 1970). Fast drying leads to warping or cracking, resulting in final rigid products with more volume and a crust on the surface (Potter and Hotchkiss, 1998). Although these products present better reconstitution properties, they are more likely to get spoiled. On the other hand, slow drying rates result on uniform and denser products (Brennan, 1994), with reduced re-hydration rate and capacity (Karathanos *et al*., 1996). As previously remarked, loss of water is accompanied by loss of internal pressure; cellular tissue loses volume and becomes flacid. This pressure is known as turgor pressure and plays an important role in the rheological and textural properties of the tissue.

Mechanical tests can be applied to quantify textural attributes of dried foods. Dynamic tests, such as compression, relaxation and creep are the most used ones (Krokida *et al*., 2000b).

Karathanos *et al.* (1994), using stress relaxation tests on raisins, found that reduction of water content decreased the viscous character, and that a decrease in sugar content causes an increase in their elastic nature. Similarly, apple subjected to convective drying presented a loss in elasticity and became more plastic as the water content decreased (Lewicki and Lukaszuk, 2000). Krokida *et al*. (2000a), when studying dried apple, banana, potato and carrot, observed a decrease in maximum stress during drying, followed by an increase, probably due to developing crystallinity (after a critical water content). Some authors concluded that raisins are viscoelastic bodies, mainly due to the elastic behaviour of the skin (Karathanos *et al*., 1994; Lewicki and Spiess, 1995), which is also determinant to breakage resistance.

Several models have been formulated to describe the rheological behaviour of different fruits and vegetables. A three-element Maxwell model was proposed by Karathanos *et al.* (1994) to fit values of stress in order to relaxation time of raisins. Compression tests on apple, banana, carrot and potato, were performed by Krokida *et al*. (2000a), who applied a mathematical model proposed by Foutz *et al.* (1990) to adjust experimental values of stress in order to strain and water content of the product. In a wider research, Krokida *et al.* (2000b) studied plasticity and elasticity of apples subjected to different drying methods.

Lewicki and Spiess (1995) used an exponential equation to fit values of stress in order to strain, resulting from compression tests with raisins. In a qualitative analysis, these authors observed the following phenomena during the compression tests: rearrangement of internal structure of the berry, flow of solution high in sugars, stretching of the skin and smoothing out of wrinkles.

FINAL REMARKS

Relating physical properties, and particularly texture, with microstructure is a relatively new area. Although this is a wide working field, much is still to be done.

Correlating microstructure, texture measurements and sensory analysis would be an attractive area to be exploited for drying processes of fruits and vegetables. The use of videomicroscopy and image analysis is an interesting non-invasive technique deserving to play an important role in drying studies.

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