Structural Changes During Air Drying of Fruits and Vegetables

I.N. Ramos, T.R.S. Brandão and C.L.M. Silva*

Escola Superior de Biotecnologia, Universidade Católica Portuguesa
Rua Dr. António Bernardino de Almeida, 4200-072 Porto, Portugal

This work aims at reviewing structural changes occurring in convective air drying of fruits and vegetables. These include changes in physical properties, such as volume, porosity and bulk and particle density, which directly affect textural attributes of the products. Models relating with water content physical properties are also summarised. At microscopic level, the phenomena observed by previous authors is described, focusing on shrinkage. In particular, a new approach on modelling kinetics of microstructural modifications is presented. Although the air drying process is relatively well studied, there is a lack of research concerning changes in structural properties. Modelling mass transfer during drying frequently does not include those effects and, there has not been established a standard methodology for predictive purposes. Correlating microstructure, texture measurements and sensory analysis would be an attractive area to be exploited for drying processes of fruits and vegetables. Although this is a wide working field, much is still to be done.

Key Words: microstructure, texture, drying, fruits, vegetables

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 the word "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 main 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.

Drying is a relatively well-studied subject, however there is a lack of information concerning structural changes during the process. This paper aims at overviewing existing studies related to structural changes during drying of fruits and vegetables, among others, changes in volume, porosity and density that directly affect textural attributes and microstructural characteristics of the products.

*To whom correspondence should be sent
(e-mail: crislui@esb.ucp.pt).

MICRO AND MACROSTRUCTURAL CHANGES

Drying processes lead to changes of foods at microstructural level, consequently it affects 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, during fast drying processes, the product surface dries much faster than its core, a phenomenon that originates internal stresses that results in very cracked and porous product interior (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 in potato drying experiences.

Microstructural studies may improve the understanding of drying mechanisms and the knowledge of food properties, and provide not only qualitative information, but also 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 visualise a small region of transparent sample. The information obtained from the microscope is then suitable for quantification using a software for image analysis (Aguilera and Lillford, 1997). Scanning electron microscopy and image analysis have been used in apple drying analysis (Bolin and Huxsoll, 1987) and light microscopy for studying structural changes in potato during drying (Wang and Brennan, 1995). However these techniques are not commonly used in drying studies. More recently, Ramos et al. (2002) applied stereo-microscopy to investigate microstructural modifications during drying on grapes and observed disruption of cellular walls, cellular collapse, increase of brilliance with increasing liquid water at the surface at the beginning of drying, and shrinkage during drying (Figure 1).

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. The shrinkage 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 and it is a relevant factor to be accounted for establishing drying models.

Reeve (1943) and Crafts (1944) reported pioneer studies of shrinkage at microscopic level, related to dehydration processes of carrots, potatoes and several fruits. 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). General empirical shrinkage models have been proposed for fruits and vegetables during drying (Suzuki et al., 1976; Vagenas et al., 1990; Madamba et al., 1994; Zogzas et al., 1994) as a function of water content of products. Ramos et al. (2002) studied grape microscopic shrinkage, quantifying several parameters directly related to cellular dimensions.The parameters of cellular area, perimeter, major axis, minor axis and Feret diameter were fitted as a function of time and temperature (Figure 2). A first order model and the Arrhenius equation for the temperature effect were used to fit experimental data, aiming the estimation of activation energy and reference drying rate. Relating microscopic with macroscopic shrinkage, and generally, microstructure with texture and physical properties, is an interesting field of research.

PHYSICAL PROPERTIES

The most important physical properties, that characterise the quality of dried 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 processes 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

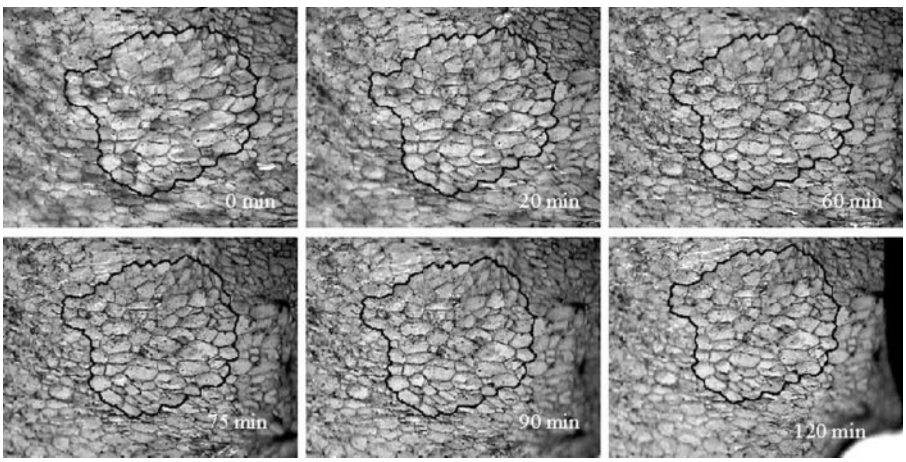

Figure 1. Shrinkage of grape cells at 30 °C as a function of drying time.

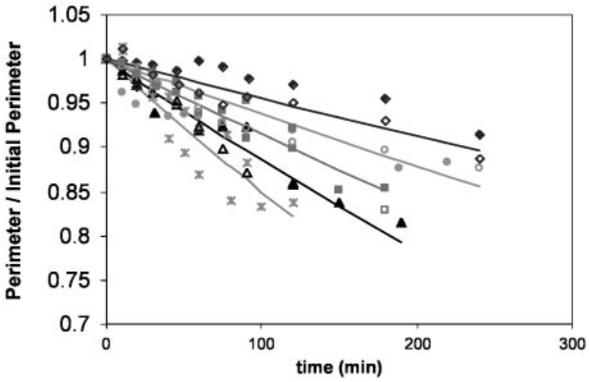

Figure 2. Experimental cellular perimeter of air drying grape and model predicted values (continuous lines) as a function of time and temperature (empty icons are replicates). (◆) 20 °C; (●) 30 °C (■) 40 °C; (▲) 50 °C; (∗) 60 °C.

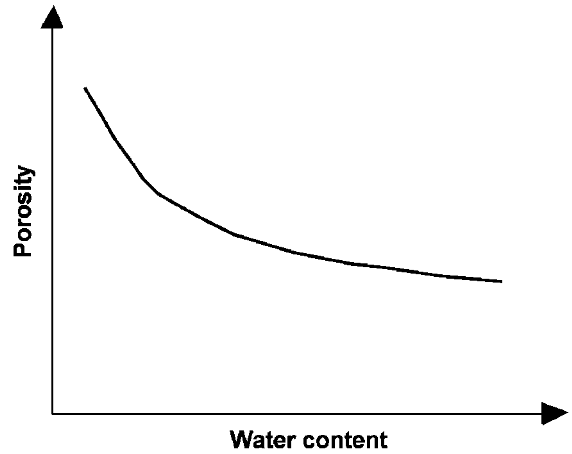

Figure 3. Typical variation of porosity with water content.

Table 1. Models relating porosity (ε) with water content (X, kg water/kg dry solid), for air dried fruits and vegetables.

Model		Food Product
$\varepsilon = 1 - \dfrac{a_1 - a_2 \exp(-a_3 X)}{a_4 \exp(-a_5 X)}$	(1)	Apple, pear, carrot, potato, sweet potato and garlic cylinders (Lozano et al., 1980)
$1.5 < X < 7.45$ g/g		
$\varepsilon = 1 - \dfrac{a_1 - a_2 \exp(a_3 X)}{a_4 \exp(-a_5 X) - b_1 \exp(-b_2 X)}$	(2)	Apple, carrot and potato cubes (Zogzas et al., 1994)
$X < 1.5$ g/g		
$\varepsilon = 1 - \rho_{bo} \dfrac{(1/\rho_s) + (X/\rho_w)}{1 + \beta X}$	(3)	Avocado, prune and strawberry slices (Tsami and Katsioti, 2000) Banana, apple, carrot and potato cylinders (Krokida and Maroulis, 1997)
where β is the volume-shrinkage coefficient		

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 the increase of surface exposition (Potter and Hotchkiss, 1998).

During drying, the product porosity increases as the water and volatiles are removed (Figure 3). However, Krokida and Maroulis (1997) stated that the porosity of the final product could be controlled, if an appropriate drying method is chosen. Air-dried products have 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). Air-dried carrots and potatoes developed almost negligible porosity when compared with apples (Zogzas et al., 1994). These authors derived also a mathematical model, correlating porosity with water content. A review of equations used to model the variation of porosity, of air dried fruits and vegetables, is presented in Table 1.

Besides porosity, pore size and pore size distribution of a food are important structural characteristics. Karathanos et al. (1996) performed studies on porous structure, 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

Table 2. Models relating particle density (ρ_p) with water content (X, kg water /kg dry solid), for air dried fruits and vegetables.

Model		Food Product
$\rho_p = c_1 \exp(-c_2 X)$ $1.5 < X < 7.45$ g/g	(4)	Apple, pear, carrot, potato, sweet potato and garlic cylinders (Lozano et al., 1980)
$\rho_p = c_1 \exp(-c_2 X) - d_1 \exp(-d_2 X)$ $X < 1.5$ g/g	(5)	Apple, pear, carrot, potato, sweet potato and garlic cylinders (Lozano et al., 1983)
$\rho_p = e_1 + e_2 \frac{X}{X_o} + e_3 \exp(-e_4 \frac{X}{X_o})$	(6)	Apple, carrot and potato cubes (Zogzas et al., 1994)
$\rho_p = \frac{1+X}{(1/\rho_s) + (X/\rho_w)}$	(7)	Avocado, prune and strawberry slices (Tsami and Katsioti, 2000) Banana, apple, carrot and potato cylinders (Krokida and Maroulis, 1997)

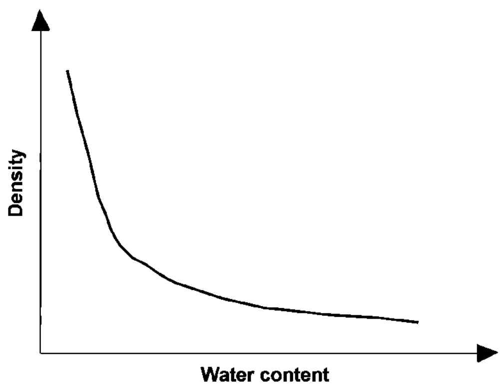

Figure 4. Typical variation of density with water content.

pores (Lewis, 1987). It is 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 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; Table 2). It was observed that, as water content decreases, the particle density increases (Figure 4). However, apples and carrots, followed a peculiar behaviour consisting on an inverted tendency for lower values of water content (Lozano et al., 1980, 1983). 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). A typical variation of this property with water content is represented in Figure 4. This tendency was observed by several authors (Lozano et al., 1983; Madamba et al., 1994; Zogzas et al., 1994; Wang and Brennan, 1995; Krokida and Maroulis, 1997) dealing with drying of carrot, pear, banana, potato, sweet potato and garlic. In some cases, and similarly to 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, and Wang and Brennan (1995) explained it as consequence of a decrease of shrinkage in the final stages of drying. Karathanos et al. (1996) observed an almost constant bulk density of carrots, not varying with water content. The models found in literature to describe the dependence of bulk density with water content are summarised in Table 3.

TEXTURE

Texture is a difficult property to define. It can be considered an external reflection of micro and macro-structural 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

Table 3. Models relating bulk density (ρ_b) with water content (X, kg water/kg dry solid, or W, kg water/kg matter wet basis) for air dried fruits and vegetables.

Model		Food Product
$\rho_b = f_1 - f_2 \exp(-f_3 X)$	(8)	Apple, pear, carrot, potato, sweet potato and garlic cylinders (Lozano et al., 1980)
$\rho_b = g_1 + g_2 \frac{X}{X_o} + g_3 \exp\left(-g_4 \frac{X}{X_o}\right)$	(9)	Apple, pear, carrot, potato, sweet potato and garlic cylinders (Lozano et al., 1983)
$\rho_b = \rho_{bo} \frac{1+X}{1+\beta X}$	(10)	Apple, carrot and potato cubes (Zogzas et al., 1994)
$\rho_b = h_1 + h_2 W - h_3 W^2$	(11)	Avocado, prune and strawberry slices (Tsami and Katsioti , 2000) Banana, apple, carrot and potato cylinders (Krokida and Maroulis, 1997) Garlic cloves (Madamba *et al*., 1994)
$\rho_b = i_1 + i_2 \exp(i_3 X^2)$	(12)	Potato slabs (Wang and Brennan, 1995)

(Potter and Hotchkiss, 1998). Although these products present better reconstitution properties, they are more likely to be 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 soft. 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).

Stress relaxation tests on raisins revealed that reduction of water content decreased the viscous character, and that a decrease in sugar content caused an increase in their elastic nature (Karathanos et al., 1994). This behaviour has led to consider raisins as 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. 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) observed a decrease in maximum stress values during drying of apple, banana, potatoes and carrots followed by an increase, probably due to the development of crystallinity (after a critical water content).

Several models have been formulated to describe the rheological behaviour of different fruits and vegetables. Karathanos et al. (1994) proposed a three-element Maxwell model of fit values of stress versus relaxation time of raisins. A mathematical model developed by Foutz et al. (1990) according to the strain and water content of the product, was fit to experimental values obtained by compression tests on apples, bananas, carrots and potatoes (Krokida et al., 2000). 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, resulting from compression tests with raisins. These authors observed during the compression tests a rearrangement of internal structure of the berry, a flow of solution high in sugars, a stretching of the skin and a smoothing out of wrinkles.

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