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Sweet Potato: Production, Morphological and Physicochemical Characteristics, and Technological Process

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ABSTRACT

Sweet potato (*Ipomoea batatas* L.) shows great socio-economic importance, providing a supply of calories, vitamins and minerals for human nutrition. Roots present a carbohydrate content varying between 25 and 30%, which 98% is easily digested. Sucrose is the most abundant sugar in raw roots, with a small amount of glucose and fructose. They are also excellent sources of carotenoids, potassium, iron and calcium and phenolic compounds. Sweet potato roots vary in shape, size and color, depending on the cultivar and environment conditions. This crop is amongst the 15 largest agricultural productions and can be used as raw material for several industrialized products, considering its composition and agricultural potential. Its shelf life is no longer than a few weeks and therefore it is difficult to stockpile in farms. Industrial processes is required to reduce its moisture content and osmotic dehydration is a technique that can be used for concentrating the solids by immersing roots in the solution of sugar and/or salt increasing osmotic pressure. However, a complementary process is required such as drying or freeze-drying to obtain a product with a lower water activity. High temperature short time (HTST) drying is also highly appropriate for processing of high starch content foods such as tubers. This method promotes the formation of a porous structure and consequently crispy food, thus making it possible to compete with high quality and makes it possible to industrialize differentiated products, which can be consumed directly or used as part of formulas, such as instant soups. This chapter is divided into: (i) description of physical-chemical and morphological characteristics, botanical aspects, production and consumer market information, (ii) conservation methods applied for maintaining nutritional and organoleptic properties of this biological product for longer periods, and (iii) sweet potato starch as a food ingredient.

Keywords: post-harvest technology, convective drying, HTST drying, osmotic dehydration, freeze-drying, microscopy

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INTRODUCTION

Sweet potato (*Ipomoea batatas* L.) shows great socio-economic importance, providing a supply of calories, vitamins and minerals for human nutrition. The roots present a carbohydrate content varying between 25 and 30%, of which 98% is easily digested. They are also excellent sources of carotenoids, potassium, iron and calcium (Clark *et al.* 1988).

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Invited Review

Their roots are tubers and vary in shape, size and color, depending on the cultivar and the environment in which they are produced (Soares *et al.* 2002; Miranda 2005).

This crop is amongst the 15 largest agricultural productions at approximately 123.5 million tons (world production). Asian production corresponds to about 87% of this amount, China being the largest world producer with 100 million tons (FAOstat. 2006).

Sweet potato can be used as a raw material for several industrialized products, considering its composition and agricultural potential. However, in Brazil and in the greater part of the world, this culture is restricted to direct consumption and industrialization is rudimentary, the best known product in Brazil being a conserve known as "marrom-glacê".

The Brazilian Table of Food Composition –TACO (Tabela Brasileira de Composição de Alimentos – TACO), produced by the Food Studies and Research Nucleus - NEPA, of the University of Campinas - UNICAMP, shows that the sweet potato contains a lot of calories, is rich in carbohydrates and has a high content of potassium and other mineral salts (Nepa 2006).

According to Unifesp (2008), the leaves of the sweet potato are also very nutritious and can be prepared like any other leafy green vegetable. The recently picked roots usually have a low soluble solids content that tends to increase during storage due to the action of the amylolytic enzymes (Ruiz 1984). The sweet potato contains between 16-40% dry mass, of which 75-90% are carbohydrates made up of starch, sugar, cellulose, pectin and hemi-cellulose. Sucrose is the most abundant sugar in the raw sweet potato, with a small amount of glucose and fructose. Due to their relative abundance, the carbohydrates increase the caloric value of the sweet potato (Bouwkamp 1985), with starch being the main source.

The shelf life of the potato is no longer than a few weeks and therefore it is difficult to stockpile in farms. The roots are usually picked and eaten during the short period of the harvesting season. Thus an extension to its shelf life would make it possible to lengthen the period of commercialization, as well as improving food safety and producer income. Due to these factors, the sweet potato should be eaten within a few weeks after harvest, or processed to reduce its moisture content, which allows it to be stored for a longer period of time. They are usually dehydrated after slicing to improve the efficiency of the process (Chen 2002). It is a well known fact that in some African areas the root is sliced and dehydrated to increase conservation (Oirschot *et al.* 2003).

One of the industrial processes shown to be very efficient in obtaining nutritious products is osmotic dehydration, which is a technique used for the concentration of solid foods, either whole or cut into pieces, and immersed in an aqueous solution of sugar and/or salt at high osmotic pressure. However, this process can be classified as a preliminary stage in food dehydration, requiring a complementary process such as drying or freeze-drying to obtain a product with a lower water activity (Sankat *et al.* 1996; Mújica-Paz *et al.* 2003).

Another very interesting process is high temperature short time drying (HTST drying), highly appropriate for the processing of high starch content foods such as tubers. This method is used to promote the formation of a porous structure and consequently crispy food, thus making it possible to compete with the high quality, albeit expensive products, obtained from freeze-drying. This process makes it possible to industrialize differentiated products, which can be consumed directly or used as part of formulas that need to be reconstituted, such as instant soups.

After HTST drying, the product usually needs to be submitted to an additional drying process to reach the desired moisture content. The product resulting from the second process presents advantages such as: ease of conservation; stability of the aromatic components at room temperature for long periods of time; protection against enzymatic and oxidative degradation; reduction in weight; economy of energy as no cooling is needed; and product availability at any time of the year.

Botanical aspects

Sweet-potato is a tuberous root plant, produced on a large scale in tropical and subtropical countries. Originally from the Central and Southern Americas, it was taken to Europe by the Spanish and Portuguese and arrived in China in the 16th century. It is mostly cultivated for its roots, which are highly appreciated as food. They can be classified according to the format, size, internal color, precocity, leaf color and even by the color of the flowers. Although perennial, the sweet-potato is cultivated as an annual crop and is characterized by storing nutritious reserves in its roots, leading to immense food and industrial potential (Peixoto and Miranda 1984).

Differences amongst cultivars certainly affect the nutritional quality of the sweet potato, with variations in the ascorbic acid, protein, vitamin B, carotene and mineral contents (Bouwkamp 1985).

There are four sweet potato types in Brazil, classified according to the color of the pulp: 1) white-potato, also known as Angola or new-earth, that has a very dry pulp and is not very sweet; 2) yellow-potato, similar to the previous one, but with a sweeter flavor; 3) purple-potato, with purple skin and pulp, whose flavor and pleasant aroma are more appreciated and which is excellent for the preparation of conserves; and 4) sweet-reddish-potato, known in the Northeast Area of Brazil as "coração-magoado" (upset-heart), with a dark skin and yellow pulp. Good quality sweet potatoes have a clean, firm surface, with no cuts or insect bite marks, nor indications of rot (Hortifrutigranjeiros 2002).

Contrary to the common potato, which is a tuber belonging to the *Solanaceas* family, based on its botanical classification, the sweet potato belongs to the Fanerogam type, Angiosperms sub-type, Dicotiledonea class, *Convolvulaceae* order, *Ipomoea* gender and *Ipomoea batatas* L. species.

It is an extraordinary plant in terms of its multiplication processes. Besides producing flowers and generating fruit with seeds that are used to carry out genetic improvement, it is able to produce roots and seedlings from several parts of the plant through vegetative multiplication processes called cloning methods. Based on these methods, the plants are identical to the mother-plant, thus forming plantations with uniform characteristics (Brune *et al.* 2005).

Sweet potato has a tender vine that grows in contact with the soil, impeding erosion and the growth of harmful plants. The species has two different types of root: the round oblong or longer shaped reserve root or tuber, the one of commercial interest due to its concentration of starch and other nutritious reserves; and the absorbent roots, responsible for the absorption of water and nutrient extraction from the soil (Soares *et al.* 2002).

Amongst the crops used as feed, the sweet potato shows the greatest efficiency in terms of captivation of solar energy, mainly because of its great capacity to produce dry matter over a long period of time (Hahn 1977).

Agricultural traits

Sweet potato is a tropical plant and can be planted up to the 40° latitude, North or South. However its harvest performance is greater in humid, sunny regions, where the warm season lasts for at least four months with an average temperature of 20°C. Its resistance to drought is considerable, although it can support irrigation well, mainly in permeable lands. It is not tolerant to frost (Monteiro and Peressin 1998; Soares *et al*. 2002).

Sweet potato is a cultivar that demands little in terms of soil fertility, as it is easy to cultivate, shows wide adaptation, high tolerance towards drought and a low production cost (Miranda *et al.* 1987). It prefers the loose, sandy or mixed

Table 1 Average composition of the fresh sweet potato mentioned by several authors.

Components	Unit	A	B	C	D	E
Moisture content	%	70.0	73.0	59.1 - 77.7	68 - 70	70.0
Protein	g/100 g	1.0	2.0	2.0 - 2.9	4.13	-
Total Lipid	g/100 g	0	0	0.3 - 0.8	0.87	-
Cholesterol	g/100 g	0	-	-	-	-
Carbohydrate	g/100 g	28.0	24.0	13.4 - 29.2	90.13	33.5
Dietary fiber	g/100 g	2.6	3.0	1.3 - 3.8	2.19	2.9
Ash	g/100 g	0.9	1.0	0.6 - 1.7	2.68	1.0
Energy	kcal/100 g	114.0	105.0	110.0 - 125.0	-	-
Minerals						
Potassium	mg/100 g	340.0	204.0	273.0	-	420.0
Phosforus	mg/100 g	36.0	28.0	49.0	-	-
Calcium	mg/100 g	21.0	22.0	30.0	-	-
Magnesium	mg/100 g	17.0	10.0	24.0	-	-
Sodium	mg/100 g	9.0	13.0	13.0	-	-
Iron	mg/100 g	0.4	1.0	0.8	-	-
Manganese	mg/100 g	0.2	-	-	-	-
Zinc	mg/100 g	0.2	-	-	-	-
Copper	mg/100 g	0.11	-	-	-	-
Selenium	mg/100 g	-	1.0	-	-	-
Sulfur	mg/100 g	-	-	26.0	-	-
Vitamins						
Thiamine	mg/100 g	0.06	-	0.10	-	-
Riboflavin	mg/100 g	< 0.02	-	0.06	-	-
Ascorbic acid	mg/100 g	-	23.0	25.0 - 40.0	40.0	-
β-carotene	mg/100 g	-	-	1.0 - 12.0	0.512	0.682

(A) Nepa (2006), (B) Unifesp (2008), (C) Soares *et al.* (2002), (D) Ruiz (1984), (E) Antonio (2006).

soils that encourage good root, plant and crop development. Stony lands and very compact soils should be avoided, especially those that suffer from flooding (Monteiro and Peressin 1998).

Sweet potato scarcely reacts to the mineral fertilization carried out during the harvest year. It should be planted in rotation with more demanding cultures such as green vegetables, to take advantage of the residual effect of the previous fertilization. Production can improve with the use of organic or green fertilizer (Soares *et al*. 2002). Crop rotation is necessary to avoid a marked drop in production (Monteiro and Peressin 1998).

Sweet potato should be planted in plats, 80 to 90 cm wide, and a height of 30 cm. Crop treatment is carried out to eliminate weeds and earth encroachment on the plants, using common furrowers or weeding machines. With the growth of the foliage, the weeds should be manually pulled, without damaging them (Monteiro and Peressin 1998; Soares *et al*. 2002; da Silva 2005).

Post-harvest

For domestic use the sweet potato should be picked as soon as it reaches the ideal size for commercialization, which usually occurs between 100 and 120 days for an early harvest and after 180 days for a late harvest. For industrial use, it can be picked later.

In small areas harvesting should be carried out using a reversible moldboard harvester, although this demands the previous removal of foliage so as not to get entangled with the machine. Potato harvesting is carried out by hand, after which a scratcher can be used to turn over the earth and remove the potatoes.

Improvement and storage

After harvest, the potatoes can be washed and dried in the shade in a dry and fresh environment, and then classified. When storage is necessary this should be done in dry, well-aired areas which are not affected by bad weather.

Brecht (2003) describes sweet potatoes harvesting by cutting the vines and digging for the roots, usually using a mechanical harvester. Some mechanical diggers can dig for the roots, sort them out and load them onto trailers. Less sophisticated machines lift the roots and deposit them on the soil surface for manual collection. Irrigation is typically interrupted 2 to 3 weeks before harvest so that the vines begin to dry before they are removed and the roots harvested. Low soil moisture makes digging the roots easier and also reduces the chances of decay causing organisms that infect the roots via harvest-inflicted wounds.

The roots are easily cut, skinned, and bruised during harvest. In addition, since all roots must be cut or snapped from the plant, they all have open, broken ends that serve as sites for water loss, infection and decay. Roots should ideally be harvested during the coolest part of the day and shaded until arrival at the packinghouse or storage facility. Even so, the dug roots should not be left exposed on top of the soil for more than about 1 h to avoid sunscald. Excessive handling is avoided by harvesting sweet potato roots directly into storage crates or bins and placing them directly into the storage facility for curing (Brecht 2003).

Proximate composition

TACO produced by the Food Studies and Research Nucleus of the State University of Campinas (NEPA/UNICAMP), shows that sweet potatoes contain a lot of calories, are rich in carbohydrates and possess a high content of potassium and other mineral salts (Nepa 2006).

Table 1 presents the average composition of the fresh sweet potato as published by: (A) TACO (Nepa 2006); (B) The State University of São Paulo (Unifesp 2008); (C) and Soares *et al.* (2002); (D) Ruiz (1984) and (E) Antonio (2006).

The chemical composition of sweet potato roots shows that they are rich in carbohydrates (mainly starch) ranging 13.4-29.2%, with 4.8-7.8% reducing sugars and presenting 110 to 125 calories/100 g. It also presents a good amount of vitamin A, some components of the vitamin B complex (thiamine, riboflavin and niacin) and water (59.1-77.7%), with low protein (2.0-2.9%) and fat (0.3-0.8%) contents. As a source of minerals, the sweet potato supplies the following amounts/100 g: calcium (30 mg), phosphorus (49 mg), potassium (273 mg), magnesium (24 mg), sulfur (26 mg) and sodium (13 mg). According to data from Unifesp (2008), the leaves of the sweet potato are also very nutritious and can be prepared as any other green leafy vegetable.

The chemical composition of the sweet potato depends on the variety, soil type and period of cultivation (Ruiz

1984). The fresh roots usually possess a low soluble solids content that tends to increase during storage due to the effect of amylolytic enzymes. The fresh sweet potato contains between 16 and 40% of dry mass, and of this total 75 to 90% corresponds to carbohydrates, made up of starch, sugar, cellulose, pectin and hemicellulose (Bouwkamp 1985).

Morphological and physicochemical properties of sweet potato starch

Starch is considered to be the main component of the sweet potato root, followed by the simple sugars such as sucrose, glucose, fructose and maltose. In the food industry, starch is used to improve the functional properties and applied to soups, meat sauces, candies, puddings, salad dressings, pharmaceutical compositions, natural resins and biodegradable thermoplastic materials (Cereda *et al.* 2001).

1. Starch structures

Starch is the main component of a food diet due to its functional properties, both in the raw and modified forms, and is widely used in the production of food on account of its low cost. It is a renewable, biodegradable and non-toxic raw material, made essentially of α-D-glucose polymers (Fennema 1996).

Starch is the most important reserve material of superior plants and occurs in the form of small white granules, distributed in several places throughout the plant, mainly in aerial storage organs such as those in the pea, bean, corn, rice, wheat, barley, oats and sorghum; in those below the surface, such as in tubers (potatoes) and roots (sweet potato, cassava, arrowroot, yams) and in the stem (sago) (Swinkels 1985).

2. Composition, size and shape of the starch granules

The granules, which are specific for each plant, are mainly made up of 2 α-polyglucans known as amylose and amylopectin, which have different physicochemical properties. The proportion of amylase to amylopectin varies with the botanical source of the starch.

The size of the starch granules varies from 1 to 100 μm depending on the origin of the starch. Most of the granules are oval, although they present round, spherical, polygonal and also irregular shapes. When observed under a scanning electronic microscope (SEM), all the granules present a flat surface with no cracks (Hoover 2001).

Bermudez (1997) and Hoover (2001) verified the size and the shape of the starch granules of some tubers. In the case of the sweet potato, the size of the granules varied from 2 to 42 μm and the shape could be classified as circular, oval or polygonal. However, Leonel *et al.* (2004) showed that starch granules of the sweet potato presented circular and polygonal shapes, with the maximum diameter varying from 45 to 52 μm and the minimum diameter between 6 and 8 μm, whilst Yadav *et al.* (2006) showed that the starch granules were spherical with a size varying from 4 to 26 μm.

Antonio (2006) observed the cellular structure of the yellow sweet potato (*Mona Lisa* variety) using optical (**Fig. 1**) and scanning electronic (**Fig. 2**) microscopy. A great number of starch granules were observed in the cells, a fact confirmed by the high percentage of carbohydrates present in the raw material.

Figs. 1A, **B** and **C** show the structure of the sweet potato dyed with saffranin, a dye that shows up the cell wall. In **Fig. 1D** the pigment used was a lugol solution, which shows the presence of carbohydrates in the sample, i.e. the starch granules. The image was taken transversally to the fiber growth, and thus the cell organization around the conductive bunches (stained in red, **Fig. 1A**) could be seen. The parenchyma was made up of a variety of differently shaped cells with variable diameters containing numerous starch granules. **Fig. 1B** shows that the cell wall was thick, the

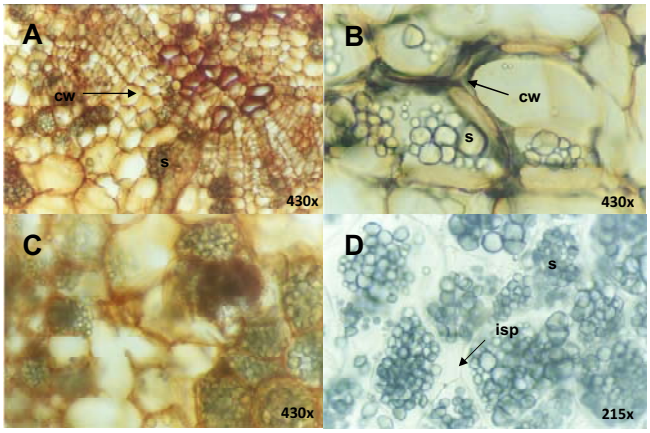

Fig. 1 Optical microscopy images of fresh sweet potato. Granules of starch (s); intracellular space (isp); cellular wall (cw). Source: Antonio (2006).

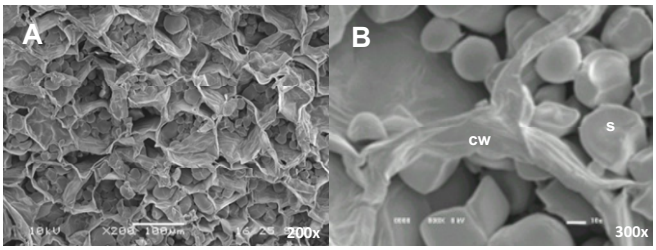

Fig. 2 Scanning electronic microscopy images of fresh sweet potato. Starch granules (s), cellular wall (cw). Source: Antonio (2006).

intracellular space limited and there were several dispersed starch granules in the cytoplasm. These granules had an oval and rounded shape presenting various sizes and an eccentric hilum. **Fig. 2** shows that the cells possessed round shapes, a very large amount of starch granules (*s*), and the cell walls (*cw*) were continuous and relatively thick (about 10 μm) and the intercellular space (*isp*) small.

3. Functional properties of the starch granules

The changes in starch structure as a consequence of dissolution and gelatinization are affected by the water/starch ratio, heating rate, morphology, amylase/amylopectin ratio, shear forces, granule and size distribution, addition of sugar, salt and protein and other factors. Mestres *et al.* (1996) commented that the starch properties depend mainly on their physical state in the food. This state changes during the heating-cooling cycle of the granule: with cooking, it changes from a granular structure to a dispersion, and during cooling and storage, it alters to a gel.

The gelatinization temperature of a sweet potato starch granule is between 57 and 90°C, showing 68% solubility at 90°C (Hoover 2001).

The high water retention capacity of the granules is due to the loss of the starch polymer organization in the native granule (Soni *et al.* 1990). This property is important in the production of extruded products such as snacks, cookies, etc.

Production and consumer market

Sweet potato cultivation is characterized by small scale production, as a secondary activity in the agricultural units of many countries. For this reason, it is an activity that generally uses inadequate production technology and technical orientation in its production, resulting in low quality and productivity indexes. In addition, the occurrence of disease and pests and the lack of pre-selected cultivars can lead to both low productivity and quality.

Cultivation of the sweet potato is of low cost and easy

maintenance, which makes it very popular with the population and of great social importance, contributing decisively to the food supply of the poorest populations. According to data from the Food and Agriculture Organization of the United Nations - FAO (FAOstat 2006), this tuber is cultivated in 114 countries, and approximately 87% of the production is from Asia, 10% from Africa and the remaining 3% from the rest of the world. Only 1.5% of the production is in industrialized countries such as the United States and Japan. China stands out as the largest producer, reaching 100 million ton/year. In the Latin-American continent, Brazil appears as the main producer, corresponding to an annual production of 500.000 tons, obtained in an estimated area of 46.000 ha (Soares *et al.* 2002; da Silva *et al.* 2005; FAOstat 2006).

Sweet potato is consumed in several ways, mainly directly with no industrial processing. The most traditional method is simple cooking, consumed with or without the use of seasonings, substituting bread and other starchy foods. The cooked and mashed potato is used in the making of conserves and salty dishes such as: purée, pastry and savory pies, and also candies, cakes, puddings, sweet pies, glazed sweets and several other products, as the main ingredient or as a partial substitute for the wheat flour.

Sweet potato is widely used due to its ease in cultivation, rusticity and wide adaptation. The crop is a socially and economically important culture considering its effective participation in the food supply. Moreover, the sweet potato constitutes an excellent alternative for animal feed and for agribusiness. Amongst the several uses of the sweet potato, the tuber can be included in "ready-to-use" products, aimed at supplying the fast food market and retail sections (Moretti *et al*. 2002). The possibility of producing pregelatinized flours, pre-cooked cereals and snacks (Borba 2005) should also be considered, besides its participation in the production of starch, alcohol and their derivatives.

In Asia, particularly in India, Japan and China it is common to find commercial starches on the market obtained from various tropical tubers such as arrowroot, sweet potato, yam, etc. (Cereda *et al.* 2001). In Peru, sweet potato flour is used as a wheat substitute in the production of bread. Similar to cassava, the sweet potato can be transformed into starch or flour, using practically the same processing procedure and with the same destination.

The shelf life of the raw sweet potato is no longer than a few weeks. Stockpiling on farms is difficult and the roots are usually picked and consumed during the short planting season. However, an extension of the shelf life could extend the commercialization time of this root, as well as improving food safety and producer income. It is known that in some African areas this tuber is sliced and dehydrated to extend its conservation.

As mentioned above, sweet potatoes should be consumed promptly after harvest, or processed in order to reduce the moisture content, allowing for storage for a larger period of time.

DEHYDRATION METHODS

The first register of dehydration know-how involving vegetables was published in the XVIII century. Later, industrial dehydration developed as a consequence of wars around the world. In 1919, some of the products processed in the United States were green beans, cabbage, carrots, celery, potatoes, spinach, turnips and soup mixtures (Vega-Mercado *et al.* 2001).

Several food dehydration methods can be found in the literature, such as osmotic dehydration; convective air drying; HTST (high temperature short time) drying and freeze-drying. These processes can be applied to several products and used separately or together in order to obtain a final product with better nutritional quality and sensory characteristics.

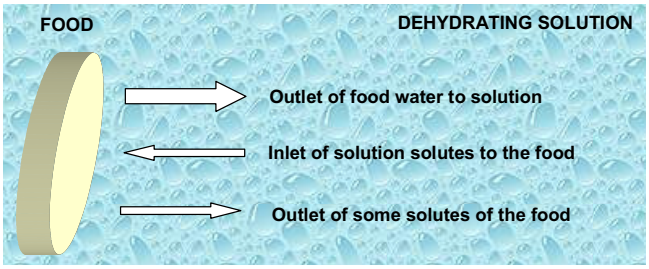

Fig. 3 Main flows during the process of osmotic dehydration. By GC Antonio.

Osmotic dehydration

Osmotic dehydration is a simple process used for the partial removal of water from several foods such as fruits, vegetables, meat and fish. It is used for solid foods, either whole or cut into pieces, immersing them in a hypertonic aqueous solution (dehydrating solution), usually made from a sugar or salt. As a consequence of the concentration gradients, two main simultaneous counter-current flows occur: (1) water that flows from the food to the aqueous solution and (2) transference of solutes from the solution to the food (Jayaraman *et al*. 1987; Park *et al*. 2002; Alves *et al.* 2005; Antonio *et al.* 2006). **Fig. 3** illustrates the mechanism described.

In addition to these two flows, a third flow also occurs, but in smaller proportions, that of the loss of some natural solids from the food, such as sugars and minerals amongst other nutrients, to the dehydrating solution. Although this third flow is proportionally insignificant when compared to the two main flows, it can be important with respect to the sensory (aroma, color, texture) and nutritional (mineral and vitamin) qualities of the final product (Jayaraman *et al*. 1987; Park *et al*. 2002; Antonio *et al.* 2008).

The main flows are responsible for creating an adverse environment, not only for the growth of microorganisms and enzymatic activity, but also for alterations in flavor and for causing an increase in sample density simultaneously with a small decrease in its volume (mainly due to water loss). The loss of water from foods mainly affects the texture, while the addition of solids coming from the solution affects the aroma and the flavor of the food (Torreggiani *et al.* 2001).

The osmotic dehydration process tends to chemical equilibrium between the dehydrating solution and the cell, and the speed of water loss from the product is greater than the speed of the addition of solids (Kowalska *et al.* 2001).

The distinctive aspect of osmotic dehydration, when compared to other dehydration methods, is the incorporation of solutes without modifying food integrity. Based on the food characteristics, it is possible to change its formulation and make it more appropriate for subsequent processing methods/procedures. For example, ingredients or additives such as antioxidants or other preservatives can be incorporated into the food, adding nutritional or sensory solutes (Torreggiani *et al.* 2001).

The osmotic dehydration process is frequently used as a pre-treatment, following by a complementary process (convective air drying, vacuum drying, freezing, etc), which could lead to a reduction in energy costs and improvements in the sensory quality of the product. This process has been used with success as a pre-treatment for a lot of fruits and vegetables, such as apples, apricots, bananas, mangos, papaya, pineapples, potatoes and carrots (Azuara *et al.* 1992; Raoult-Wack *et al.* 1994).

Using a 50 to 75% concentration for the dehydrating solution, the removal of water in the osmotic process usually varies from 40 to 70% (w/w); whilst the incorporation of solutes is between 5 and 25% (w/w) in relation to the initial product. However, a weight reduction above 50% is not recommended in an osmotic dehydration process, due to a decrease in the osmotic rate with increase in time (Raoult-Wack *et al.* 1994).

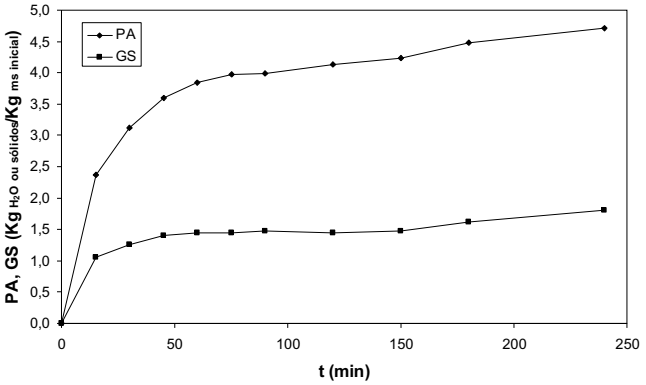

Fig. 4 Water loss of and solid gain kinetics in the optimum condition of the osmotic dehydration of sweet potato slices. Source: Antonio (2006).

Antonio (2006) carried out a study on the osmotic dehydration of yellow sweet potato (cultivar 'Mona Lisa') slices using Response Surface Methodology. The water loss, solids addition and water activity were analyzed during the process (120 min), considering the temperature (30-50°C), sucrose concentration (40-60% w/w) and salt concentration (0-10% w/w) of the osmotic solution as the independent variables. The author observed that the sucrose and salt concentrations, followed by the temperature, were the most significant factors for water loss and solids addition. However, with respect to the water activity, the effects of the salt and sucrose concentrations were more pronounced than the solution temperature. The optimized condition for maximum water loss and minimum solids gain was 40°C, 50% (w/w) sucrose and 5% (w/w) salt, considering the levels used. **Fig. 4** presents the curves of the kinetics for osmotic dehydration under the optimized condition.

The author also observed that the levels of water loss were higher than the incorporation of solids, reaching 43 and 16%, respectively. It was shown that the incorporation of solids tended to stabilize quickly during the initial hours of dehydration, whilst the water loss only stabilized after a longer processing time. This behavior has been reported by other authors during the osmotic dehydration of several other products.

Operational process variables

Studies on the osmotic dehydration process have been carried out, changing the geometry and thickness of the samples, the exposure time, the dehydrating agents and their concentrations, and considering different food matrix types.

In general the literature shows that the water loss in fruits increases with increasing solute concentration of the osmotic solution, immersion time, temperature, solution/sample ratio and food contact area, and also with the use of vacuum (Jayaraman *et al.* 1987; Kowalska *et al.* 2001).

1. Characteristics of the vegetable tissue

The cell membrane and cell wall can influence the mass transfer phenomenon. The relationship between the water loss and incorporation of solids, resulting in a weight reduction, is due to the specific action of the cell membranes in the osmotic dehydration process (Raoult *et al.* 1989).

The cell membrane is very permeable to water, and there are a few substances that easily pass through it. When placed in a hypotonic solution, the cell volume increases due to water penetration. If the increase in volume is very marked, the membrane bursts and the cell contents leak out. To the contrary, if the cells are placed in a hypertonic solution, the decrease in volume is due to the exit of water. In isotonic solutions, the cell volume and shape do not alter as long as the plasmatic membrane is impermeable to the solute (Junqueira *et al.* 1977).

The water loss and solids gain rates depend, in first place, on the properties of the vegetable tissue. The blanching, freezing, ripening and enzymatic actions are factors that directly affect the characteristics. Differences in these characteristics, such as compacting, the initial mass of non-soluble substances, presence of enzymes, dimension of the intracellular spaces, presence of gas in the capillaries, occurrence of pectin and cellulose complexes and the level of gelatinization, determine the kinetics of the dehydration process (Torreggiani 1993).

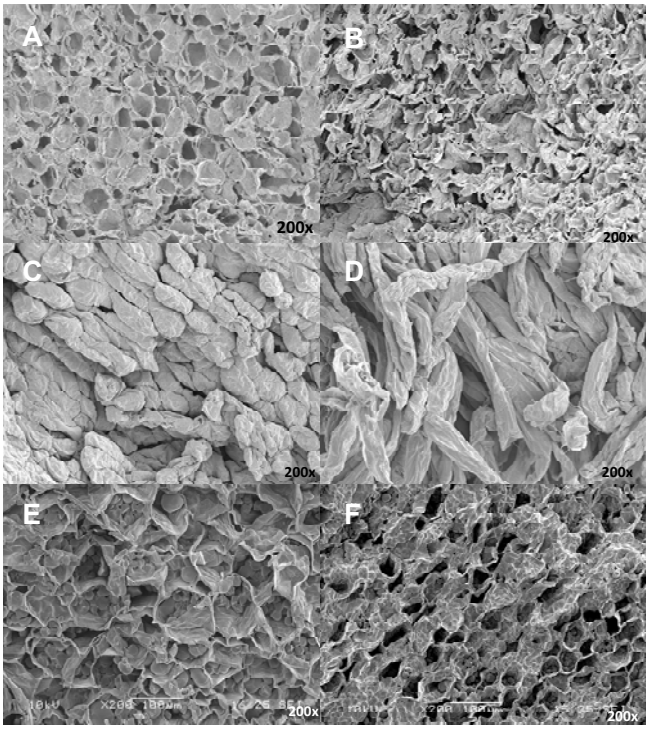

Fig. 5 Scanning electronic microscopy images. (**A**) fresh papaya fruit; (**B**) osmotically dehydrated papaya fruit (30°C, 45 °Brix); (**C**) fresh banana fruit; (**D**) osmotically dehydrated banana fruit (30°C, 45 °Brix); (**E**) fresh sweet potato and (**F**) osmotically dehydrated sweet potato (40°C, 50% (w/w) sucrose and 5% (w/w) salt). Sources: Antonio (2002, 2006).

Antonio (2002) observed a loss in turgidity in the tissues treated in the osmotic dehydration of papaya (*Carica papaya* L.) and banana (*Musa cavendish*) due to the water loss caused by the osmotic treatment, which was justified by destruction of the cell wall and by changes in membrane permeability. These observations, obtained by scanning electronic microscopy, can be visualized in **Fig. 5A** to **D** where the cell structures of both fresh and osmotically dehydrated fruits are presented. The cell structure of the fresh papaya fruit (cv. 'Formosa') possesses uniformly sized rounded cells with corrugated walls and a small intercellular space. Due to the conditions of the osmotic dehydration process (30°C, 45°Brix and plate geometry), the tissue lost part of its integrity, showing a considerable decrease in cell turgidity. The structure of fresh banana fruit (cv. 'Nanica') presented elongated cells with reduced intracellular separation, and corrugated walls can also be observed, although with a turgid aspect and certain cell alignment. When the fruit was submitted to an osmotic process (30°C, 45°Brix and plate geometry) the cells became disordered, decreasing the intracellular space; however, there was no rupture of the cell wall as a result of the low temperature applied in the process.

The cell structures of the fresh sweet potato and the osmotic dehydrated product (40°C, 50% (w/w) sucrose and 5% (w/w) salt) obtained by Antonio (2006) are also presented in **Fig. 5**. The cells are full of starch granules and the osmotic process led to a pre-gelatinization of the starch and decrease in cell turgidity.

2. Osmotic agent

The selection of the osmotic solution solutes is based on three main factors: (1) sensory characteristics of the product; (2) cost of the solute and (3) molecular weight of the solute (Karel 1975; Lerici *et al.* 1985). The most widely used dehydrating agents are sucrose for fruits and sodium chloride for vegetables. Other osmotic agents such as glucose, lactose, glycerol, ethanol and hydrolyzed corn starch syrup are also used.

The kind of solute greatly affects the mass transfer kinetics in the osmotic dehydration. An increase in molecular weight of the osmotic agent provokes a decrease in solids incorporation and an increase in water loss, favoring weight loss (Torreggiani 1993; Dalla Rosa *et al.* 2001).

3. Concentration of the osmotic solution

The water removal rate in osmotic dehydration depends strongly on the concentration of the dehydrating solution. An increase in the difference in concentration between the food and the solution promotes an increase in the process rate.

Raoult-Wack *et al.* (1994) highlighted an interesting effect of the concentration gradients on the predominance of mass transfer; when the initial concentration difference between the solution and the fruit is up to a value of 40%, solute incorporation prevails; above this value, water loss predominates, or in other words, dehydration.

The effects of temperature (26 and 50°C) and the concentration of the sucrose solution (30, 50 and 70% (w/w) on the osmotic dehydration process of sweet potato cubes (3.5 cm section) were determined by Genina-Soto *et al.* (2001). The authors reported a greater water loss and greater incorporation of soluble solids when higher solution concentrations and temperatures were used. Similar observations were made by Antonio (2006) in the osmotic dehydration of sweet potato slices.

4. Temperature

Temperature has an important influence on the kinetics of osmotic dehydration, as well as on the chemical composition and properties of the final product. This factor affects the chemical and physiochemical reaction rates, including osmosis and diffusion. A temperature increase promotes greater water removal and a decrease in dehydration time. As a consequence, the penetration of solids into the tissue also increases, however in smaller proportions.

For temperatures above 60°C, there are modifications in the characteristics of the structure, favoring the occurrence of undesirable phenomena such as vitamin losses and solids gains (Torreggiani 1993).

5. Immersion time

The water loss during osmotic dehydration is divided into two periods: (1) the initial period of approximately 2 h, with a high water removal rate and maximum solids incorporation in the initial 30 min and (2) the second period, lasting 2 to 6 h, with a decrease in the water loss rate (Raoult *et al.* 1989; Torreggiani 1993).

According to Raoult-Wack *et al.* (1994), during immersion dehydration and the impregnation of fruit and green vegetables, mass transfer occurs mainly during the first two processing hours, due to the great difference in osmotic pressure between the solution and the sample cell. After this period, transfer becomes progressively smaller until the water flow no longer takes place, while the solids incorporation invariably continues. Thus the product tends to increase its mass and become rich in the dehydrating solute.

6. Stirring

The process of osmotic dehydration is more efficient when carried out with stirring. However, this must be controlled in order to avoid damage to the product, considering the costs related to equipment, energy, etc.

Stirring guarantees that the concentrated solution is renewed around the sample creating a favorable concentration difference for mass transfer. In some cases, intermittent stirring can be enough (Raoult *et al.* 1989).

Mavroudis *et al.* (1998) studied the influence of stirring on the osmotic dehydration of apple slices. According to the authors, the water loss was greater in the area of turbulent flow than in that of laminate flow. However, with respect to the solids gain, there was no statistical difference related to the type of flow studied.

7. Food/solution ratio

The food/solution ratio is a process variable that has been studied by many authors. In general, a great rate value is used to guarantee the water/solute ratio without changes in the food/solution ratio. A great amount of dehydrating solution, a 1/5 ratio or more, is used to reach this ratio (Dalla Rosa *et al.* 2001).

Osmotic dehydration kinetics

The effect of the variables involved in the kinetics of osmotic dehydration has been investigated by several authors (Heng *et al.* 1990; Azuara *et al.* 1992; Park *et al.* 2002; Uddin *et al.* 2004; Antonio *et al.* 2008) by means of determining the water loss (WL) and the solids gain (SG), which can be calculated according to the following equations:

$$WL(\%) = 100\ x\ \frac{Mw_0 - (Mw(t) - Mdb(t))}{M_0} \quad (1)$$

$$SG(\%) = 100\ x\ \frac{(Mdb(t) - Mdb_0)}{M_0} \quad (2)$$

$$PP(\%) = \frac{(M_0 - M(t))}{M_0} x100$$

$$\text{or} \quad PP(\%) = WL - SG \quad (3)$$

where: Mw_0 = initial water mass of the sample (g); $Mw(t)$ = water mass of the sample at time t (g); Mdb_0 = initial dry mass of the sample (g); $Mdb(t)$ = dry mass of the sample at time t (g); $M(t)$ = mass of the dehydrated sample (g); M_0 = initial mass of the sample (g); PP = weight loss .

In order to describe the kinetic parameters of osmotic dehydration, several authors (Kaymak-Ertekin *et al.* 2000; Park *et al.* 2002; Telis *et al.* 2004; Antonio *et al.* 2008) have used Fick's Law, in which the mass flow is proportional to the concentration gradient inside the solid.

Consider an infinite plane plate, 2 L thick, with an initially uniform distribution of water or solid (QM), submitted to osmotic dehydration under constant conditions that can be represented by Fick's unidirectional diffusion equation (Crank 1975):

$$\frac{\partial QM(t)}{\partial t} = \frac{\partial}{\partial z}\left(D_{ef}\ \frac{\partial QM(z,t)}{\partial z} \right) \quad (4)$$

and the following initial and contour conditions:

- Initial uniform moisture distribution $QM(z,0) = QM_0$;
- Concentration symmetry: $\left.\frac{\partial QM(z,t)}{\partial z}\right|_{z=0} = 0$;
- Surface equilibrium condition: $QM(L,t) = QM_e$.

Applying the average function from center to the surface,

$$\overline{QM(t)} = \frac{1}{L}\int_0^L QM(z,t)\,dz \quad (5)$$

The following analytical solution can be reached:

$$\frac{\overline{QM(t)} - QM_e}{QM_0 - QM_e} = \frac{8}{\pi^2}\sum_{i=0}^{\infty}\frac{1}{(2i+1)^2}\exp\left[-(2i+1)^2\pi^2 D_{ef}\frac{t}{4L^2}\right] \quad (6)$$

where: $\overline{QM(t)}$ = the average water or solids content after a process time (t): QM_0 = initial water or solids content; QM_e = water or solids content at equilibrium; D_{eff} = water or solids effective diffusivity; L= characteristic material dimension (half the thickness of the plate).

Analytical and empirical models have been reported to model the mass transfer phenomenon during the process of osmotic dehydration. Lenart *et al.* (1984), Raoult-Wack *et al.* (1992) and Azuara *et al.* (1996) developed empirical models. Beristain *et al.* (1990) proposed a model based on Fick's Law and Toupin *et al.* (1989) developed a complex mathematical model based on the transport phenomena.

A typical osmotic dehydration process demands several hours of processing to reach equilibrium, and, in some cases, it is impossible to reach equilibrium due to the biological and/or physical instability of the product to be dehydrated. Peleg is an empirical model, frequently used to predict the kinetics of the osmotic dehydration of biological materials (Peleg 1988). This model reports on the relationship between the amount of matter that flows during the osmotic process and the initial amount of matter, using two process parameters (Equation 7).

$$QM(t) = QM_0 \pm \frac{t}{k_1 + k_2 t} \quad (7)$$

where: k_1 and k_2 = model parameters; t = process time.

The ± sign is related to the flow direction involved in the osmotic process. The sign was stipulated as - for water loss, and + for solids gain. The linear form of Equation 7 allows one to obtain the values for the parameters k_1 and k_2 from the intersection and slope of the straight line.

According to the model, the equilibrium moisture content (QM_e), is reached when $t\rightarrow\infty$. Thus it is possible to predict the value of the water or solid losses under the equilibrium condition without taking the process to this condition.

The initial mass transfer rate (t=0) can also be obtained by calculating the inverse of k_1.

Palou *et al.* (1994) used Peleg's model in the osmotic dehydration of papaya and obtained good results for the determination coefficient, indicating that it was a good model to adjust experimental data. Sachetti *et al.* (2001), studying the osmotic dehydration of apples, and Antonio (2002), studying banana and papaya fruits, also proved the efficiency of this model.

Azuara *et al.* (1992) developed an equation capable of predicting the kinetics of osmotic dehydration, as well as determining the final point of equilibrium in order to reach equilibrium, using a short process period. Considering a mass balance of a material submitted to dehydration:

$$QM^* = QM_e^* - WS \quad (8)$$

where QM^*= water loss or solids gain during the process (%); QM_e^* = water loss or solids gain in the equilibrium (%); WS = accumulation (%).

The relationship between QM^* and WS is represented by the parameter K:

$$WS = \frac{QM^*}{K} \quad (9)$$

This parameter was calculated assuming that the water removal rate $QM^* = QM_e^* - WS$ was only dependent on time. Based on this, it was possible to propose a simple function for K in terms of the time (t) and the constant (S) reported for water loss:

$$K = S\,t \quad (10)$$

Substituting Equations 8 and 10 in Equation 9, and rearranging the terms, Azuara *et al.* (1992) obtained the following expression:

$$QM^* = \frac{S\,t(QM_e^*)}{1 + S\,t} \quad (11)$$

where: S = a constant related to water loss or solids gain (h^{-1}); t = immersion time (h).

The values for S and QM_e^* can be found from the linearization of Equation 11, presented by the following equation:

$$\frac{t}{QM^*} = \frac{1}{S(QM_e^*)} + \frac{t}{QM_e^*} \quad (12)$$

This model can be used to characterize the osmotic dehydration of different types of foods, not considering geometrical restrictions.

Crank (1975) presented a simplified equation based on Fick's Law for a plate in contact with an infinite amount of solution, considering a transient regime and short periods of time:

$$\frac{QM^*(t)}{QM_e^*} = 2\left(\frac{D_{ef}\,t}{\pi\,L^2}\right)^{1/2} \quad (13)$$

Based on Equations 11 and 13, Azuara *et al.* (1992) obtained an equation capable of calculating the effective diffusivity for water loss, considering a geometry similar to that of an infinite plate (Equation 14):

$$D_{ef} = \frac{\pi\,t}{4}\left[\left(\frac{S\;L}{1+S\,t}\right)\left(\frac{QM_e^{*\,\mathrm{mod}}}{QM_e^{*\,\exp}}\right)\right]^2 \quad (14)$$

where:

$QM_e^{*\,\mathrm{mod}}$ = the equilibrium value obtained from Equation 12;

$QM_e^{*\,\exp}$ = the equilibrium value obtained experimentally.

The diffusivity related to the process is calculated by taking the arithmetical average of the diffusivity values found at each time (Equation 15).

$$\overline{D_{eff}} = \frac{\sum_{i=1}^{\infty} D_{eff\,(i)}}{N} \quad (15)$$

where: $\overline{D_{eff}}$ = effective average diffusivity (m^2/s); $D_{eff(i)}$ = effective diffusivity at each time (m^2/s); N = number of experimental points.

Of the several models used, Equation 16 was proposed to describe the kinetics of drying corn (Page 1949). This equation is known as Page's Empirical Model and has been used by some researchers to study the kinetics of the osmotic dehydration of other food products (Park *et al.* 2002).

$$\frac{\overline{QM(t)} - QM_e}{QM_0 - QM_e} = \exp\left(-K\,t^{\,b}\right) \quad (16)$$

where: $\overline{QM(t)}$= the average water or solids content after a process time (t); QM_0= the initial water or solids content; QM_e = the water or solids content at equilibrium; b = model parameter; K = water loss or solids gain constant, t = process time.

More recently, Antonio *et al.* (2008) in a study on the osmotic dehydration of sweet potato, obtained an excellent fit with the Azuara *et al.* (1992), Peleg (1988) and Page (1949) models and a higher average relative error with the Fick's model, but below 16%.

HTST drying

HTST drying is a method that has presented good results for some fruits and vegetables, competing with high quality products obtained by freeze-drying process. This method promotes the formation of a porous structure and con-

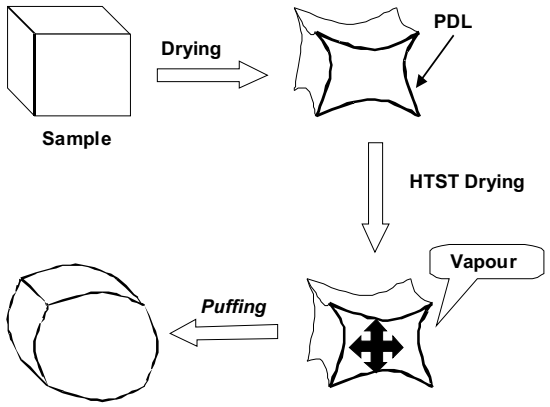

Fig. 6 Mechanism proposed for HTST drying. By GC Antonio.

sequently a crispy food.

The HTST drying process usually involves high temperature in a fluidized bed. During the process, an initial layer is formed on the surface, this partially dry layer (PDL) being necessary to achieve puffing (expansion of the product). The mechanism proposed for drying at a high temperature involves the following stages (**Fig. 6**):

- Initial drying, a stage necessary to create a layer on the surface (PDL), where a reduction in mass transfer occurs due to sealing of the surface;
- Transformation of sample moisture into steam, due to the use of a high temperature;
- Restriction to the escape of water vapor, caused by the existence of the PDL;
- Development of pressure inside the sample, which forces the inner walls out and creates a porous structure, increasing the volume of the sample;
- Conventional drying after the HTST drying process, to ensure the stability of the dry product.

The puffing process was created with the intention of searching for better rehydration characteristics of dried fruits and vegetables using conventional air drying. The process is being studied aiming at a commercial application in the processing of fruit and vegetables. The improvement of the functional properties and of the dehydration of the product, particularly with respect to the rehydration rate, is one of the main objectives of the process, besides other benefits such as an increase in the drying rate, appearance of the product, etc. The process was originally developed to work as a batch process and was later tested on foods such as: potatoes (Sullivan *et al.* 1974; Nath *et al.* 2007, 2008), apples (Sullivan *et al.* 1980; Schultz *et al.* 2007), blueberries (Sullivan *et al.* 1982), bananas (Hofsetz *et al.* 2007) and sweet potatoes (Antonio *et al.* 2008).

The HTST and conventional drying processes were used by Jayaraman *et al.* (1982) for several vegetables such as: potatoes, beans, carrots and sweet potatoes. The use of the puffing process showed a decrease in sample volume density. This decrease was very significant, presenting values of 55-60% for potatoes, 25% for beans and 35-45% for other vegetables. The HTST drying treatment at 160-180°C for 8 min applied to vegetable pieces, followed by conventional drying at 60-70°C, resulted in expansion of the product structure and a considerable reduction in the drying and rehydration times. Only the vegetables containing starch in their cellular structure reached a good expansion volume.

Torreggiani *et al.* (1995) studying the drying of apples, used an experimental design with the following independent variables: HTST drying temperature (145, 155 and 165°C), HTST drying time (6, 12 and 18 min), starch concentration (1, 2 and 3%) and pre-drying time (carried out in a hot air drying tunnel) (0, 15 and 30 min). The authors observed that sample puffing did not occur at temperatures below 145°C.

Antonio *et al.* (2008) tested this process on sweet potato slices pre-treated using an osmotic dehydration process, and submitted to convective drying as the final treatment to reach the desired final product moisture content. The authors obtained excellent results which are presented in full detail below.

Optimal processing conditions

1. Formation of the partially dry superficial layer

For the formation of a porous structure in the product and consequent puffing, a minimum initial drying is usually necessary to form the superficial layer. If the surface is moist and the PDL is not formed, the internal moisture is vaporized and leaves freely through the permeable surface of the sample, and thus puffing does not occur. The sudden moisture loss during puffing causes shrinkage of the sample. However, some foods can dispense this step.

Antonio *et al.* (2008), studying the HTST drying of sweet potato, did not carry out this step. They achieved puffing of the sweet potato slices, and verified sealing of the surface and the formation of pores inside the sample using scanning electronic microscopy – SEM (**Fig. 7**). The exclusion of this step was possible due to the great number of starch granules present in the sample, which can be seen in the SEM images and optimization of the HTST drying process.

Fig. 8 presents the core and surface structure of the fresh sweet potato slices submitted to the HTST drying process using different process conditions (110°C for 5 min and 160°C for 25 min). Considering the less drastic conditions, it could be seen that the surface structure was not totally sealed and areas with open pores and an irregular surface with reduced cell turgidity appeared, suggesting surface permeability. However, in the core of the sample, no pore formation was observed and the structure was totally irregular with a loss of cell tissue integrity and the presence of unattached starch granules. Thus puffing did not occur under these process conditions.

Nevertheless, the more drastic HTST drying condition (160°C for 25 min) resulted in the surface being totally sealed (homogeneous) due to the more severe conditions used during the process, which probably caused starch gelatinization, resulting in an amorphous glassy aspect. However, the core of the sample presented a porous structure with a large number of intact, that is, not gelatinized starch granules. Under these process conditions, intense puffing occurred.

Using SEM, Varnalis *et al.* (2001) also observed complete gelatinization of the starch granules in potato submitted to the HTST drying process. This gelatinization resulted in sealing of the surface and an increase in volume (puffing).

In the same study, Antonio *et al.* (2008) tested the use of the osmotic dehydration pre-treatment prior to the HTST drying process, for sweet potato slices. The authors verified that the sample submitted to osmotic dehydration followed by HTST drying at 110°C for 5 min presented an irregular surface with corrugated cell walls and some pores in the central part. Few starch granules and a very heterogeneous structure was observed. Under these conditions, sealing of the surface did not take place, and therefore puffing did not occur. These observations can be seen in **Fig. 8A** and **8B**.

Considering the severe conditions (160°C for 25 min), **Fig. 8C** and **8D** showed that the surfaces were more compact, however sealing did not occur satisfactorily, some fissures appeared and there was an apparent appearance of partially gelatinized starch granules. However, pore formation could be seen in the core, and some of the pores presented starch granules. With this treatment, the authors reported an increase in volume, but to a smaller degree than with the fresh sweet potato slices under the same conditions.

Antonio *et al.* (2008) concluded that for fresh samples, HTST drying was efficient and volume expansion (puffing) occurred when high temperatures (about 160°C) and longer process times (above 20 min) were used. Samples submitted

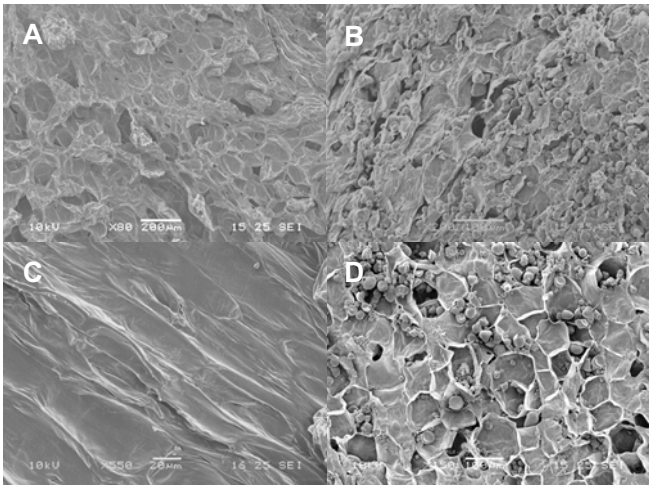

Fig. 7 SEM images of the fresh sweet potato dried by HTST. (**A**) Surface - 110°C/5 min (X80); (**B**) core – 110°C/5 min (X200); (**C**) surface – 160°C/25 min (X550); (**D**) core - 160°C/ 25 min (X150).

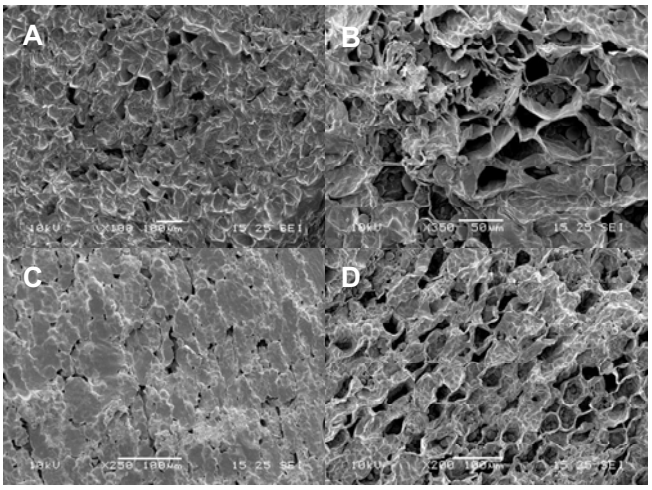

Fig. 8 SEM images of osmotically dehydrated sweet potato (40°C, 50% (w/w) sucrose, 5% (w/w) salt and dried by the HTST drying process. (**A**) Surface – 110°C/5 min (X100); (**B**) core – 110°C/5 min (X350); (**C**) surface – 160°C/25 min (X250), and (**D**) core – 160°C/25 min (X200). Source: Antonio *et al.* (2008).

to the osmotic pre-treatment prior to the HTST drying process showed non-enzymatic browning of the product (Maillard Reaction) at temperatures above 150°C when long periods of time were used, contributing to a burnt aspect besides resulting in a very hard product. Thus the best HTST drying condition was a temperature of 150°C for 10 min, although the volume was smaller than that obtained with the fresh sample.

Nath *et al.* (2008) also used SEM to visualize the changes inside the potato snack structure at the different puffing stages, showing material expansion, starch granule expansion, etc.

2. Formation of the porous structure

The presence of a porous structure in dehydrated foods with a low moisture content is highly desirable, to make them crispy. Crispiness is the sensory property characterized by several successive fractures in the product when chewed (Torreggiani *et al.* 1990). However, the formation of pores is only possible if the cell structure is strong enough to resist stress when water is removed during dehydration (Kim *et al.* 1987; Mujumdar *et al.* 1989).

The presence of starch in the product is very important during the puffing process and the gelatinization degree is dependent on the process time and temperature, and the sample moisture content (Lund 1984).

Sugars, particularly disaccharides, increase the starch gelatinization temperature. This increase limits the availability of water to the starch granules, decreasing the water activity and forming bridges between the starch chains, or neutralizes the water plasticizing action.

According to Torreggiani *et al.* (1995), the diversity of pore sizes caused by the puffing process favors water removal and resistance of the solid matrix in order to avoid shrinkage. Materials with high moisture content do not have a sufficiently strong solid matrix to resist shrinkage during the conventional dehydration process, and therefore a special process to strengthen the structure is necessary. A decrease in structure collapse during the dehydration process can be enabled by the infusion of solids or the application of an appropriate layer onto the raw material surface prior to dehydration.

Bobic *et al.* (1988) immersed the product in a gelatinized starch suspension prior to dehydration, creating a superficial layer which was impermeable to water vapor. This layer retained the steam, creating an internal pressure that caused expansion of the solids during the fluidized bed drying process. The same procedure was performed by Schultz *et al.* (2007) for HTST apple drying at temperatures of 120 and 140°C for 0.25 h followed by conventional drying at temperatures of 60 and 80°C.

Rehydration

During convective air drying, shrinkage causes irreversible changes in the texture of most foods and, when the food is rehydrated, the texture does not resemble that of the original food, remaining solid and hard. In addition, the diffusion of solids during drying causes surface hardening of the product, described as "case hardening" that demands more time during rehydration. The increase in product porosity due to application of the HTST process causes expansion and faster dehydration and rehydration of the final product.

The puffing process allows the product to acquire favorable characteristics such as an excellent flavor and color, easy rehydration, storage at room temperature, reduction in transport and storage costs and durability, besides considerably reducing the drying time (Sullivan *et al.* 1982; Kim *et al.* 1987; Payne *et al.* 1989; Antonio *et al.* 2008).

Antonio *et al.* (2008) observed that sweet potato samples pre-treated by HTST drying presented greater water addition during rehydration, which coincided with the greatest expansion. This behavior was attributed to pore formation during the puffing process.

Torreggiani *et al.* (1995) using a conventional drying process in apples verified a decrease in product quality. The tissue shrank and the cells collapsed due to water loss, hindering rehydration. However, the high temperature and short time drying process (HTST) resulted in the formation of a porous structure, presenting a considerable reduction in drying time, steady moisture content and easy rehydration.

Convective drying

Drying is one of the oldest and most common unit operations found in a wide range of agricultural, ceramic, chemical, food, pharmaceutical, paper and cellulose, mineral and polymer producing industries. It is also one of the most complex and misunderstood operations, due to difficulties and deficiencies in the mathematical description of the simultaneous phenomena involved such as heat, mass and momentum transfer in the solid. Thus, drying is a combination of science, technology and art, that is, *know-how* based on extensive experimental observations and operational experience (Menon *et al.* 1987).

The reasons for drying are as many as the number of materials that can be dried. Keey (1978) stated that a product had to be capable of being submitted to a subsequent process or had to be sold. Thus, there are materials that can

be pressed, ground or palletized at determined moisture contents. Powders need to be dried to low moisture contents in order to provide satisfactory storage. Transport costs are also reduced by removal of the greater part of the water contained in the product. Dehydrated vegetables possess an enriched flavor and can also be used in "ready-to-eat" or expensive foods (Pan *et al.* 1997).

In contrast, the quality of the dried product may be reduced, due to the use of high temperatures or prolonged exposure times that can cause vitamin and nutrient losses (Cohen *et al.* 1995).

Once the product is put into contact with hot air, the heat transfer of this to the product is due to the temperature difference between them. Simultaneously, the difference in partial vapor pressure between the air and the product surface determines the transfer of mass to the air via the water vapor. Part of the heat impinging on the product is used to vaporize the water (Park *et al.* 2007).

The factors that govern the velocity of the transfer phenomena determine the drying rate, such as the water vapor pressures of the air and that inside the material, air temperature and velocity, water diffusion velocity in the material, thickness and exposed surface.

Antonio *et al.* (2008), studying the drying of sweet potato slices (cv. 'Mona Lisa'), applied osmotic dehydration and/or HTST drying prior to convective air drying. The authors observed that the moisture content decreased exponentially with drying time under all the conditions analyzed, which is a typical behavior of biological products. In addition, the shortest air drying time was that used for the product submitted to the HTST drying treatment, followed by that without the pre-treatment. The treatments submitted to osmotic dehydration presented a longer drying time, because of the solids that were incorporated during the osmotic process.

Drying kinetics

During the drying operation, the simultaneous heat and mass transfers could be divided schematically into three periods: induction period, constant rate period and falling rate period.

1. Induction period

This is the period that takes place up to the operational regime, consisting of an adaptation of the product to the drying conditions. Initially, the product is usually colder than the air and the vapor partial pressure on the product surface is low, and consequently the mass transfer and drying velocity are also low. The heat, when present in excess, causes a temperature increase of the product, leading to increases in the pressure and drying velocity. This phenomenon continues until heat transfer precisely compensates mass transfer. If the air temperature is below that of the product, the latter will decrease until reaching the same equilibrium condition. The duration of this period is insignificant in relation to the total drying period (Park *et al.* 2007).

2. Constant drying rate

During this period, the drying rate is constant. Similar to the period mentioned earlier, the water content available inside the product is abundant. In this case, the water evaporates as if it were in an open reservoir. The water vapor pressure on the surface is constant and equal to the vapor pressure of pure water at the same temperature (Keey 1972).
This period continues whilst water migration from the inner part to the product surface is sufficient to accompany evaporation from the surface.

For biological materials, the existence of this period is hampered since the resistances to mass transfer are essentially inside the product, which means that the evaporation rate from the surface to the atmosphere is much higher than the water transference from the internal region to the surface of the material (Park *et al.* 2007).

3. Falling rate period

The falling-rate period begins at the moment when the water content is deficient on the surface of the solid and the drying velocity decreases. During this period, the heat exchange is no longer compensated and, consequently, the product temperature increases and tends asymptotically towards the air temperature. During this whole period, the limiting factor is the internal water migration. The reduction in the drying rate is due to a diminution in the partial water vapor pressure on the surface of the solid. At the end of this period, the product will be in equilibrium with the drying air and the drying velocity will be null (Keey 1972).

In food drying, the falling-rate period is observed for the majority of the period, mainly due to difficulties inside the product for the liquid water to reach the surface. The water transport mechanisms in biological materials have still not been completely explained, since the components involved, such as cells, fibers and membranes are very complex.

The diffusional theory, mainly used for agricultural products, is based exclusively on Fick's Law, which considers that the mass flow per area unit is proportional to the water concentration gradient. Substituting Fick's Law in the water mass balance equation inside the product:

$$\frac{\partial \mathrm{X}}{\partial t} = \nabla \cdot \left(D_{eff} \nabla X \right) \tag{17}$$

where: D_{eff} = Effective diffusivity (m^2/s); X = moisture content (kg_w/kg_{dm}); t = time (s).

Crank (1975) presents a large number of solutions for the diffusion equation for initial and boundary conditions. However, these solutions are applied to the solids in simple geometric forms (semi-infinite bodies; plates, cylinders and spheres) and when the diffusivity is constant or varies linearly or exponentially based on the water concentration. In rectangular coordinate systems (x, y and z), the diffusion equation is expressed as:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial x}\left(D_{eff} \frac{\partial X}{\partial x} \right) + \frac{\partial}{\partial y}\left(D_{eff} \frac{\partial X}{\partial y} \right) + \frac{\partial}{\partial z}\left(D_{eff} \frac{\partial X}{\partial z} \right) \tag{18}$$

Assuming the geometrical shape of a 2L thick infinite plane plate, where the transfer of internal moisture during drying is predominantly unidirectional and considering the constant diffusivity, the equation above becomes:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial z}\left(D_{eff} \frac{\partial X}{\partial z} \right) \tag{19}$$

Regardless of the shrinkage of the material during drying and the external resistance to mass transport, and considering that at the interface the moisture is in constant equilibrium, the boundary and initial conditions for moisture are:

Initial uniform moisture: $X(z,t) = X(z,0) = X_0$

Maximum moisture at the center: $\left. \frac{\partial X}{\partial z} \right|_{Z=0} = 0$

Constant equilibrium surface moisture: $X(z,t) = X(L,t) = X_e$

and applying: $\overline{X} = \frac{1}{L} \cdot \int_0^L X(z,t) dz$ (20)

Resulting in:

$$Y = \frac{\overline{X} - X_e}{X_o - X_e} = \frac{8}{\pi^2} \cdot \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left[-(2i+1)^2 \cdot \pi^2 \cdot D_{eff} \cdot \frac{t}{4L^2} \right] \tag{21}$$

where: D_{eff} = the effective diffusivity (m^2/s); Y = the dimensionless moisture content; $\overline{X}$ = the average moisture content (kg_w/kg_{dm}); X_e = the equilibrium moisture content (kg_w/kg_{dm}); X_0 = the moisture content at t_0 (kg_w/kg_{dm}); i = the number of terms in the series; t = time (s); L = the characteristic length, semi-thickness of the sample (m); z =

transference direction (m).

The diffusion coefficient (D_{eff}) is an effective diffusivity that includes the entire effects of the phenomena, interfering in water migration, and is always obtained from the fitting of the experimental curves. The solution to the diffusion equation is one of the simplest resolutions, explaining its wide use. Diffusivity can be understood as the ease with which water is removed from the material and varies with the changes in the drying conditions (temperature and air velocity). It is not intrinsic to the material and is thus denominated as "effective diffusivity".

Empirical models have also been used to describe the drying kinetics of several products. Lewis (1921) presented an exponential model that assumed that the drying rate was proportional to the free water content in the material:

$$\frac{dX}{dt} = -k\left(X - X_e\right) \quad (22)$$

where: k = the drying constant (s^{-1}).

Antonio (2006) used the Diffusional Model in the study of sweet potato drying with and without osmotic dehydration and/or HTST drying pre-treatment, obtaining determination coefficients close to unity and average relative error values with values below 12%. Using Page's Model, the determination coefficients were also close to unity and the average relative error values were even smaller.

PROCESSED SWEET POTATO CHARACTERISTICS

The quality of processed food is fundamental to the food industry. Quality is not only based on the visual (appearance, color) and sensory (aroma, flavor, texture) attributes, but also on the nutritional qualities of the product.

During the drying process, the food is submitted to the processing conditions (temperature, light and heat exposure) that can cause nutritional losses and sensory modifications, generating a low quality product.

To acquire a good quality product, food processing should be analyzed in order to find the conditions that best fulfill the requirements desired in the product (water activity (a_w), final moisture content, texture, aroma, flavor, etc.), with minimal nutrient losses.

According to Van Den Berg (1986), water is one of the most important factors controlling the deterioration processes, and the microbiological processes are usually the fastest. The fundamental purpose of food dehydration is to diminish the water availability necessary for the growth of undesirable microorganisms and for chemical reactions, permitting wider distribution and extended storage.

Water activity is one of the most important properties for the processing, conservation and storage of foods. It quantifies the degree of water linkage with the product and, consequently, its availability to act as a solvent and to participate in the chemical, biochemical and microbiological transformations (Labuza 1980).

The maximum value for water activity is 1, that of pure water. Therefore the water activity of a solution or food is always inferior to 1. The measurement of this property is extremely important since lipid oxidation reactions, non-enzymatic browning, enzymatic activity and microbial development, as well as the behavior of food mixtures with different water activities can be foreseen, and also appropriate packing systems can be chosen (Quast *et al.* 1975; Torrezan *et al.* 1997).

The reduction of the water activity to 0.91 inhibits the great majority of the pathogens except for *Staphylococcus aureus*. If a water activity value of 0.93 is considered desirable, a large number of pathogeneses will be eliminated and the others can be inhibited using obstacles such as pH, preservatives, redox potential and a mild heat treatment in a hermetic package, among others.

Enzymatic or non-enzymatic reactions (lipid oxidation, non-enzymatic browning) that cause color and flavor changes, continue acting during the dehydration process and storage of foods with a water activity greater than 0.70. This characteristic is a common parameter to predict food deterioration or to determine the final drying point required for a longer product shelf-life (Jayaraman *et al.* 1987).

The addition of salts, sugar and other substances leads to a reduction in water activity due to the decrease in the partial water vapor pressure. This reduction varies according to the nature of the substance(s) added, the concentration and the temperature. The water activity can also be reduced by the removal of water using processes such as dehydration or freezing.

Carotenoids are natural colorants present in fruit and vegetables (carrots, tomatoes, spinach, oranges, peaches), and their chemical structure consists of conjugated double bonds responsible for its color and some biological functions (Stahl *et al.* 1999). They are part of the natural pigment groups widely found in nature. They are responsible for the yellow to red colors of flowers, leaves, fruits, some roots, egg yolk, lobster and other crustaceans, some fish and birds.

Apart from their function as colorants, some carotenes also act as vitamin A precursors in food. According to Rodriguez-Amaya (1999a), dark green colored vegetables, palm oil, palm fruit, carrot, sweet potatoes, pumpkins and tropical fruit that have an orange coloring seem to be the most promising sources of pro-vitamin A. Since vitamin A is chemically half of the β-carotene structure with an additional water molecule at the end position, only carotenes with at least half of a non-substituted β-carotene molecule have provitamin A activity. The carotenes are highly susceptible to degradation and consequently to losses in their desirable color and provitamin activity properties.

From a processing point of view, the carotenoids possess a high degree of unsaturation, making them highly susceptible to degradation. In nature the cellular ultra-structure and complexation with proteins provide them with stability. Carotenoid stability depends on oxygen availability, temperature, light exposure, water activity, the presence of metals, acidity and the structure of the carotene (Godoy 1985; Rodriguez-Amaya 1999a, 1999b).

In spite of their susceptibility to degradation, carotenoids can be preserved during industrial processing. Processing at low temperatures for shorter times are recommended, but high processing temperatures for short times are also a good alternative (Rodriguez-Amaya 1999a, 1999b).

Potassium is an important element that makes up about 5% of the total mineral content of an organism. Thus, similar to chlorine and sodium, it is involved in the water balance and distribution, in osmotic equilibrium, in the acid - base equilibrium and in the regulation of neuromuscular activity. It also promotes cell growth. This mineral is an important electrolyte for the neurotransmitters, muscle contraction and fluid equilibrium in the organism. Symptoms of

Table 2 Water activity (a_w), carotenoids (CT) and potassium (KT) contents for sweet potato slices submitted to convective air drying process.

Sample	a_W	CT (mg/100 g)	KT (mg/100 g)
Fresh	0.984 ± 0.001	0.682 ± 0.015	420.00 ± 11.00
Convective air drying T = 50°C			
CD[a]	0.831 ± 0.002	1.07 ± 0.39	788.00 ± 27.00
OD[b]	0.690 ± 0.007	0.36 ± 0.08	654.00 ± 17.00
HTST[c]	0.564 ± 0.008	0.66 ± 0.06	921.00 ± 8.00
DO + HTST[d]	0.615 ± 0.007	0.24 ± 0.02	650.00 ± 28.00
Convective air drying T = 70°C			
CD	0.821 ± 0.006	1.18 ± 0.15	725.00 ± 21.00
OD	0.592 ± 0.003	0.60 ± 0.07	673.00 ± 21.00
HTST	0.455 ± 0.008	1.02 ± 0.12	973.00 ± 25.00
OD + HTST	0.513 ± 0.006	0.37 ± 0.09	576.00 ± 9.00

[a] CD: no pre-treatment, only convective air drying;
[b] OD: osmotic dehydration pre-treatment (40°C, 50% w/w sucrose, 5%w/w salt);
[c] HTST: HTST drying pre-treatment (160°C/25 min);
[d] OD + HTST: osmotic dehydration (40°C, 50% w/w sucrose, 5%w/w salt) prior to HTST drying (150°C/10 min).
Source: Antonio (2006).

potassium deficiency include muscle weakness, disorientation and fatigue.

Potassium is found in various fresh foods such as meat, milk, fruit, vegetables, greens, potatoes and whole grain food, as well as poultry, fish, milk and cereals.

Sweet potato presents a significant potassium content (420 mg/100 g), comparable to foods such as bananas (370 mg/100 g), raw cauliflower (395 mg/100 g), raw carrot (340 mg/100 g), and inferior to avocado (604 mg/100 g), watercress (606 mg/100 g) and nuts (715 mg/100 g).

The yellow sweet potato (cv. 'Mona Lisa') was used by Antonio (2006) to obtain a snack using osmotic dehydration and/or HTST drying pre-treatments, followed by convective air drying at 50 and 70°C (**Table 2**). It was shown that the water activity decreased with increasing air drying temperature. The HTST drying pre-treatment led to the greatest decrease in water activity at both temperatures. These findings permit the prevention of product deterioration by bacterial pathogens, since growth of these bacteria does not occur at water activity values below 0.90. However, fresh sweet potato submitted to air drying is still subject to mold development, since mold growth only ceases below 0.70 of water activity according to Bobbio *et al.* (1992).

In this study it was shown that increasing the temperature led to smaller losses in the carotenoid content for all the treatments. This fact can be explained by the smaller exposure time to heat and oxygen, causing less degradation. Comparing the OD with the CD samples, it was shown that the former presented greater carotenoid losses. This fact probably occurred due to the larger exposure time to oxygen and heat during osmotic dehydration as well as during the drying step. A reduction in carotenoid content was also observed in samples submitted to HTST drying. This reduction was still more noticeable with the use of both pre-treatments (OD +HTST).

The potassium content of the final product was high (**Table 3**), presenting an increase in relation to the raw sample due to the removal of water during air drying. This increase varied from 138 to 232%. The highest potassium contents were reached using HTST drying followed by CD treatments. Considering the OD treatment, the potassium content was smaller, which could be explained by losses occurring during the osmotic process.

In recent years, studies have focused on phenolic compounds and antioxidant activities in different parts and varieties of sweet potatoes (Rumbaoa *et al.* 2009; Shih *et al.* 2009; Jung *et al.* 2011). Antioxidative and physiological changes of freeze-dried, hot air-dried and extruded products of two different colours of sweet potatoes (yellow and orange) were investigated by Shih *et al.* (2009). The freeze-dried samples of orange sweet potatoes had more total phenolic compounds and had better scavenging effect on DPPH (1,1-diphenyl-2-picrylhydrazyl) radicals than freeze-dried yellow sweet potatoes. Both sweet potato extruded products showed higher phenolic contents than freeze-dried sweet potato samples.

SWEET POTATO STARCH APPLICATIONS AS A FOOD INGREDIENT

Rheological properties

Sweet potatoes are an economical and healthy food crop containing high carbohydrate contents, β-carotene, substantial amounts of ascorbic acid and minerals as mentioned before. Globally, the sweet potato is an important food which is used for industrial applications such as dietary fiber, pureed infant food, spray-dried powders and thickeners (Lii *et al.* 2003; Ahmed *et al.* 2006; Grabowski *et al.* 2008). This product has advantages as a food ingredient in relation to other cereals, especially with respect to wheat, due to its hypoallergenic effect. In general sweet potato is converted into flour to preserve the product, to be used in formulations for soups, sauces, snacks, chips, noodles and breads.

Studies on the rheological properties are important for process design and development, to evaluate the sensory properties and to widen the applications of sweet potato-based material.

The rheological properties are considered to be important analytical tools to provide fundamental insights into the structural organization of food and they play an important role in heat transfer. Some foods, especially starches and proteins, undergo changes/modifications during processing, resulting in a viscous dispersion, solutions or gel, depending on the temperature and concentration (Li *et al*. 2010). In general, fluids containing suspended particles have a certain structure, which is sensitive to shearing. Hence, steady-shear viscosimetry is not ideally suited if one wishes to probe the rheological characteristics of an unperturbed dispersion (Ahmed *et al.* 2006). In oscillatory rheometry, the specimen is subjected to a very small oscillatory stress, such that its structure remains intact. The small-amplitude oscillatory tests (dynamic) have been commonly used to characterize the viscoelastic behavior of foods and allow researchers to relate the dynamic rheological parameters to the molecular structure and glass transition temperatures of the sample (Gunasekaran *et al.* 2000).

Many workers have studied the rheological parameters of sweet potato flour dispersions (Nnam 2001; Chun *et al.* 2006; Grabowski *et al.* 2006, 2008) and have stated that the rheological properties of the flour dispersions depend on the concentration, temperature and additional treatments using amylases to reduce the viscosity prior to the drying process.

Sweet potato puree has been dried commercially by drum-drying into dark brown, compact flakes with poor solubility. In contrast, spray-drying offers several advantages for dried sweet potatoes and the resulting powder presents an improved quality, and can be easily dispersed in water and readily incorporated into food products (Masters 1991). However, the viscosity of the puree is a challenge in spray-drying due to its thick and sticky characteristics that hinder pumping and atomizing during the operation cycle. Previous authors have reported the reduction of sweet potato puree viscosity by the use of elevated temperatures, addition of water and use of alpha-amylase in order to aid

Table 3 Syneresis of starch gels (%) from conventional and non-conventional sources during the five freeze-thaw cycles.

Starch*	1st cycle	2nd cycle	3rd cycle	4th cycle	5th cycle
C	9.87 ± 1.25 $^{B, c}$	25.29 ± 2.22 $^{B, b}$	37.24 ± 0.26 $^{A, a}$	36.96 ± 4.70 $^{A, a}$	37.41 ± 0.06 $^{A, a}$
WC	1.01 ± 0.06 $^{C, bc}$	0.61 ± 0.13 $^{D, c}$	1.85 ± 0.51 $^{E, bc}$	6.66 ± 2.82 $^{C, a}$	7.81 ± 2.51 $^{C, a}$
CF	0.94 ± 0.09 $^{C, c}$	0.88 ± 0.08 $^{D, c}$	9.36 ± 0.50 $^{D, ab}$	11.54 ± 0.06 $^{B, C, a}$	8.31 ± 1.49 $^{C, b}$
CP	19.51 ± 0.72 $^{A, b}$	27.92 ± 2.86 $^{B, a}$	21.65 ± 1.51 $^{C, ab}$	19.53 ± 1.32 $^{B, b}$	21.64 ± 1.87 $^{B, ab}$
WB	24.81 ± 1.86 $^{A, c}$	33.97 ± 0.75 $^{A, a}$	28.84 ± 0.33 $^{B, bc}$	29.64 ± 0.51 $^{A, ab}$	33.01 ± 1.00 $^{A, a}$
PC	0.96 ± 0.16 $^{C, c}$	1.45 ± 0.56 $^{C, bc}$	2.71 ± 1.06 $^{E, abc}$	4.66 ± 0.02 $^{C, ab}$	3.80 ± 0.39 $^{C, a}$
SP	0.47 ± 0.01 $^{C, d}$	1.76 ± 0.28 $^{D, cd}$	1.89 ± 0.01 $^{E, bc}$	2.93 ± 0.23 $^{C, b}$	16.74 ± 0.26 $^{B, a}$

*C = native corn, WC = waxy corn, CF = modified waxy corn, *Col Flo 67*®; CP = chickpea, WB = white bean, PC = Peruvian carrot, SP = sweet potato.

** Means and standard deviations of three replicates.

$^{A-E}$ Mean values in the same column with different letters are significantly different ($p \leq 0.05$).

$^{a-f}$ Mean values in the same line with different letters are significantly different ($p \leq 0.05$).

Source: **Takeiti C, Fakhouri F, Ormenese R, Steel C, Collares F** (2007) Freeze-thaw stability of gels prepared from starches of non-conventional sources. *Starke/Starch* **59**, 156-160, with kind permission of the authors.

the control of the process and produce consistent sweet potato puree notwithstanding seasonal and storage variations (Szyperski *et al.* 1986; Kyereme *et al.* 1999).

Researchers have demonstrated that the spray-drying of any high sugar food is inefficient, due to the product sticking to the walls of the drying chamber (Bhandari *et al.* 1997; Vega *et al.* 2005). Food products containing substances with low molecular weights, such as sugars, have very low glass transition temperatures (T_g), so these components can depress the T_g of the entire system (Roos *et al.* 1991). If the temperature of the spray-dried particles is greater than 20°C above the glass transition temperature of that product, the particle will exhibit a sticky behavior (Bhandari *et al.* 1999).

Grabowski *et al.* (2006) reported that it is desirable to keep the viscosity of a material to be spray-dried below 0.25 Pa.s in the spray dryer feed. Thus these workers used a combination of high temperature and alpha-amylase treatment to reduce the viscosity of sweet potato puree prior to spray-drying and observed that an increase in temperature from 25C to 90°C reduced the viscosity from 5.10 to 2.59 Pa.s. These workers also stated that the addition of water is not an efficient means of viscosity reduction, since extra energy would be required to remove the additional liquid. Likewise, pretreatment of the puree with alpha-amylase prior to spray-drying had significant effects on particle size and hence on bulk density. The particle size decreases with increasing amylase treatment, which could be attributed to the action of alpha-amylase in decreasing the feed viscosity. Since the atomization energy remained constant, the atomized droplet may decrease in size and therefore decrease the final particle size, which has a tremendous impact on bulk density.

The same authors (Grabowski *et al.* 2008) reported that comprehension of the rheological properties of the reconstituted powders would be useful for potential product applications. The flow behavior of the sweet potato powder solutions was similar to that of pre-gelatinized starch solutions. All the reconstituted solutions were shear-thinning and displayed slight thixotropy in contrast to the flow behavior of the puree, which best fitted the Herschel–Bulkley model, presenting pseudoplastic behavior with a yield stress at the same solids concentration. Although sweet potato powders in solution performed similarly to pre-gelatinized starch solutions, they required higher concentrations for the same effects.

Similar results were reported by Chun *et al.* (2006) who studied the steady and dynamic shear rheological properties of different concentrations (6, 7, 8, 9 and 10%) of sweet potato flour dispersions. The steady shear rheological properties showed non-Newtonian behavior, with yield stress of the sweet potato flour dispersions at 25°C at different concentrations. The flow behavior index (n) values decreased (0.41 to 0.31) with increasing concentration (6 to 10%), indicating that the higher shear-thinning performance observed at higher concentrations was due to a high content of high molecular weight substance (starch) in the liquid phase, and it was also noted that the rheological parameters obtained from flow models showed dependency on the concentration of the sweet potato flour dispersions. Considering the effects of the concentration (8%) and temperature (25, 40, 55 and 70°C) on the apparent viscosity, the values decreased with increasing temperature, which can be attributed to the increase in intermolecular distances as a result of thermal expansion with increasing temperature.

In addition, the dynamic shear rheological properties revealed dominance of the elastic properties over the viscous properties, and the dispersions became more elastic with increasing concentration. The elastic properties observed can be attributed to the intermolecular association of amylose chains leaching out from the granules. Based on the dynamic data, 6-10% dispersions of sweet potato displayed weak gel-like behavior that could be explained by the association of ordered chain segments, giving rise to a weak three-dimensional network.

Dynamic mechanical spectroscopy and steady-shear rheological tests were carried out to evaluate the viscoelastic properties of commercial sweet potato puree infant food (Ahmed *et al.* 2006). The results were in agreement with those of previously mentioned authors, and, as expected, the puree behaved as an elastic solid. The effects of temperature on the elastic (G') and viscous (G'') moduli of sweet potato were found to be in the ranges of 146–319 and 22–73 Pa, respectively, at temperature ranges from 5 to 80°C. The values for G' decreased from 5 to 80°C except at 65°C, while G'' decreased systemically. According to the authors, starch gelatinization at 65°C could be the reason for the increasing values of G', and the phenomenon was explained on the basis of weak hydrogen bonding and strong hydrophobic interaction during thermal processing and gel formation. The steady flow parameters of sweet potato puree indicated the presence of yield stress and a good fit of the data to the Herschel–Bulkley model. The flow behavior index (n) ranged between 0.34 and 0.54 with no systematic trend with temperature.

The same authors used Differential Scanning Calorimetry (DSC) in an attempt to verify correspondence of the rheological measurements with the structural changes. During the heating of baby food, the starches (amylose and amylopectin) and possibly some of the additives in association with water exhibited order–disorder phase transitions (gelatinization). Two thermal peak transitions (57 and 94.5°C) were observed for sweet potato puree, and the first peak corresponded to gelatinization of the starches. The second thermal transition could be attributed to the presence of other ingredients and/or the disorganization of the amylose–lipid complexes, as revealed by endothermic transition at temperatures (95–130°C) well above the melting endotherm of starch crystallites (Kugimiya *et al.* 1980).

Sweet potato contains 75–80% amylopectin and 20–25% amylose and gelatinization of this starch, contrary to the puree, presents a single stage type ranging from 75 to 85°C (Zaidul 2008). Delcour *et al.* (2000) concluded that the slight changes in the starch gelatinization behavior were caused by lipid or protein removal or by differences in the granule size distribution, and would have a negligible effect on pasta quality i.e. affecting the gelatinization peak temperature.

In food processing, gelatinization and pasting of starch granules occur during the heating process along with shearing, leading to changes in the starch granules and viscosity. Retrogradation occurs during cooling, due to re-association of the starch molecules, leading to the formation of a gel due to the increase in viscosity. Native starch pastes often suffer from low stability to shear or other mechanical moduli. During distribution and storage, starch pastes suffer transformation of the starch biopolymer molecules: namely, chain aggregation and re-crystallization. Moreover, it is difficult to maintain frozen food products in a constant and optimum frozen state if they undergo repeated freeze–thaw cycles during the supply chain, leading to changes in syneresis and related rheological properties (Lee *et al.* 2002). This is the driving force in the food industry, to formulate and develop high quality products whose quality can be maintained throughout processing, distribution and storage (Pongsawatmanit *et al.* 2008).

Freeze-thaw cycles

The systematic search for ready to eat food products has brought about a significant increase in the range of frozen products offered on the market. According to Rahman (1999), water turns into ice during freezing causing damage to the food structure, and when this food is thawed for consumption, the water quickly leaches from the product, altering the texture and causing a loss of overall quality.

Starch has been used in a wide range of "ready-to-eat" pre-processed and frozen products. Nevertheless, in order to maintain the final quality of the product, the starch must maintain its characteristics and present low syneresis indi-

ces. Stability to freezing and thawing cycles is defined as being the ability of the starch to resist the physical changes which occur during the freezing and thawing phases, being used as an indicator of the tendency to retrogradation (Schoch 1968) and determining the potential use of starches in frozen products (Baker *et al.* 1998).

Retrogradation of gelatinized starch is a process that involves its two basic components: amylose and amylopectin, the retrogradation of amylose being faster than that of amylopectin. The process depends on a number of variables, including: temperature; concentration; type of starch and presence of other ingredients (Jacobson *et al.* 1997). During freezing, phase separation occurs with the formation of ice crystals. During thawing, two aqueous phases coexist, one rich in starch and the other with a lower content of starch. The greater the number of freeze-thaw cycles, the greater the phase separation, due to the occurrence of retrogradation of the amylopectin present in the starch rich aqueous phase, according to Yuan *et al.* (1998). During thawing, the water is easily separated from the processed food matrix. This phenomenon is known as syneresis, and is related to starch retrogradation, as shown by Karim *et al.* (2000).

Recently, several studies have reported the freeze–thaw cycles of some starch gels (Lee *et al.* 2002; Jobling 2004; Karim *et al.* 2007; Takeiti *et al.* 2007; Wischmann *et al.* 2007; Charoenrein *et al.* 2008; Wang *et al.* 2008). In its native state, starch has a limited number of uses, mainly as a thickener or binder. On heating in water, the granule starts to swell, increasing the viscosity of the solution. Further heating and stirring leads to disintegration of the granule structure, dissolution of the starch and a loss of viscosity, and on cooling, the linear chains re-associate into aggregates, precipitate and set to form a gel. Controlling this process is a key factor in starch functionality, which is achieved mainly by the chemical modification of the starch when it is in the granular state. Thus modified starches have been obtained by: (i) technological modifications by the addition of charged groups to the chains, stabilizing the gel formation; (ii) *in planta* modifications with the use of mutants and genetic changes. In this particular case, mutation of the *Waxy* locus, which encodes the granule-bound starch synthase (GBSS) protein, creates a starch that has no amylose (Jobling 2004). Due to their lack of amylose, waxy starches have improved freeze–thaw stability compared to normal starches (Zheng *et al.* 1998). From the consumer perspective and environmental point of view, it would be advantageous if freeze–thaw stability could be engineered without the use of chemical treatments according to Jobling (2004).

Considering this point of view, Takeiti *et al.* (2007) stated that non-conventional native starches, like the Peruvian carrot (*arracacha*) and sweet potato, could be considered more stable to freeze-thaw cycles, with properties similar to the commercial starches due to the reduced syneresis presented. The freeze-thaw stability of these starches is excellent, as can be seen in **Table 3**. Syneresis was observed for all the starches studied but to different extents. Waxy corn starch, modified waxy corn starch, sweet potato and Peruvian carrot starches lost less water than native corn, chickpea and white bean starches. During the whole experiment, the Peruvian carrot starch gel lost, at most, 5% water, and the waxy corn and modified waxy corn starches, 8 and 12%, respectively. Significant differences in the second and fifth freeze-thaw cycles were also observed between the tubers. For the sweet potato gel, syneresis only reached approximately 16% in the last cycle, while for the Peruvian carrot gel it was 3.8%, indicating a better application of these starches in frozen products. These values are lower than those found by Lee *et al.* (2002) for sweet potato starch, already in the first cycle (32%). The latter authors stated that thermal energy fluctuation and phase changes of the water during the freeze-thaw treatment were the probable causes of disruption of the starch gel matrix. This behavior leads to unavoidable water loss. In order to minimize syneresis, the same authors added different types of gum to sweet potato gel, obtaining less syneresis when guar

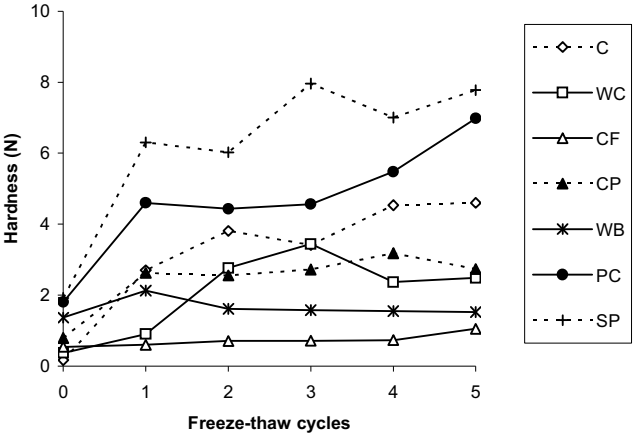

Fig. 9 Hardness of starch gels from conventional and non-conventional sources during five freeze-thaw cycles. C = native corn, WC = waxy corn, CF = modified waxy corn, *Col Flo 67*®; CP = chickpea, WB = white bean, PC = Peruvian carrot, SP = sweet potato. Source: **Takeiti C, Fakhouri F, Ormenese R, Steel C, Collares F** (2007) Freeze-thaw stability of gels prepared from starches of non-conventional sources. *Starke/Starch* **59**, 156-160, with kind permission of the authors.

gum and xanthan gum were added at concentrations of 0.3 or 0.6% (w/w, based on the total gel weight). The results obtained in this study confirmed that starches with greater contents of amylopectin presented less syneresis. This observation is in agreement with Coninck (1999), who claimed that waxy corn starches presented good resistance to retrogradation due to the high amylopectin content.

Despite the low syneresis values, the hardness (**Fig. 9**) of the tuber starch gels was higher than that of the remaining starch gels, already presenting a great increase in the first freeze-thaw cycle. The hypotheses to explain this increase in hardness could be related to the chemical and physical structures of the gels formed, as influenced by the freeze-thaw cycles, and are apparently not only related to retrogradation. The authors proposed further analyses, including the determination of chemical, physical (morphology) and rheological (gelatinization) properties to investigate and explore these aspects of the gels after frozen storage.

Wang *et al.* (2008), studying chestnut starch gels, also noted a significant increase in gel hardness after the 1st cycle (6.8 times higher) as compared to the control, followed by a gradual decline in hardness which appeared in the 2nd and 7th freeze-thaw cycles. This performance was explained considering that the initial development of firmness was due to amylose gelation, and the subsequent increase in network rigidity due to starch re-crystallization. The increase in gel hardness could be due to the formation of a network structure whereas the first decline could be ascribed to large ice crystals in the starch gels; or to the cooperation of rearranged starch molecules and the collapsed starch gel structure. During the repeated freeze-thaw cycles, the amylose and amylopectin were rearranged in an ordered manner. The results of X-ray diffraction and the thermal and textural analyses, indicated that the amylose rearrangement mainly induced changes in the physicochemical properties and microstructure of the starch gels before the 4th freeze-thaw cycle, while the re-association of the amylopectin interfered with the amylose rearrangement after the 4th freeze-thaw cycle. The authors also noted that there was a turning point with respect to the physicochemical properties and microstructural changes at the 4th freeze-thaw cycle, decreasing gel hardness.

Likewise, Lee *et al.* (2002) observed that the matrix structure only changed after three freeze-thaw cycles. In this case, the sweet potato starch gel presented a thick fibrillar network forming a spongy-like structure with relatively larger cavities than those found in the gum-added gels. The size of the cavities varied according to the type

and concentration of the gum used, and were more significant at the higher gum concentration (0.6%). The change in gum concentration resulted in a difference in ice crystal size. The greater the amount of gum added (0.6% of xanthan), the larger the ice crystals formed. As a result, the microphotographs showed that syneresis of the starch gel was positively related to the size of the ice crystals produced.

Finally, sweet potatoes present high crop productivity and their cultivation should be stimulated to reduce their cost in developing countries. This could make native starches from non-conventional sources an excellent alternative for application in frozen products without any chemical modification, in contrast to the modified corn and cassava starches produced by food manufacturers. Sweet potato starch could be used in food formulations where a small sponge-like structure is needed, such as in bakery products, and could probably be used at lower concentrations since its harder texture limits the specific application. It could also undoubtedly be applied in frozen products in view of the fact that it supports repeated freeze-thaw cycles.

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