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Predicting the Impact of Food Processing on the Physical Properties of Food

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Abstract

The physical properties of food play a significant role in the modeling and computation of the heat and mass transfers in basic food processing operations. With the advent of improved analytical techniques, statistical experiment design applications, computing ability and knowledge of the food physical properties of food, there have been significant advances in our ability to predict the impact of processing on the physical properties of food. This article briefly reviews our current ability to predict the influence of processing on the physical properties of food, such as water activity, moisture, color, and rheological characteristics.

Key words: water activity, color, rheological property, food processing, review

INTRODUCTION

The physical properties of food play a significant role in the modeling and computation of the heat and mass transfers in basic food processing operations, such as drying, thermal processing and freezing (1). The exploration of the physical properties of foods, and their responses to process conditions, are crucial in analyzing unit operations, because these affect the qualities of products and are also good indicators of other properties. Better control of both products and their processing would therefore be possible, and these have benefits for the producer, industry and the consumer (2).

In addition, knowledge of these properties should constitute important engineering data in the design of processes and controls, in developing new consumer products and in evaluating the quality of the final product. Such basic information is essential not only to engineers, but also to food scientists and processors. Despite increasing interests and applications, information on the basic physical properties is limited. Thus, this paper briefly reviews the impact of food processing on selected physical properties of food, such as water activity, moisture, color and rheological property.

WATER ACTIVITY AND MOISTURE

Water is an important constituent of all foods. Water activity, a thermodynamic property, is defined as the ratio of the vapor pressure of water in a system to the vapor pressure of pure water at the same temperature, or the equilibrium relative humidity of the air surrounding the system at the same temperature (3). During the storage and processing of agricultural products, physical, chemical and microbiological changes occur, and these changes are particularly influenced by the moisture content of the material, the water activity and the storage temperature.

Physical properties of water activity

The relationship between the water activity and moisture content of a product is often expressed as a sorption isotherm. The typical shape of an isotherm reflects how the water is bound to the system. In cases were the water activity is below 0.30, the water is considered to be held on polar sites, called monolayers, which have relatively high energies. Water activities in the range of 0.30~0.70 are referred to as multilayer water, which consists of layers of water, adsorbed onto the first layer by hydrogen bonds. If the water activity is above 0.7, the water approaches the condition of "condensed water", which is relativity free water, and the isotherm reflects solution and surface capillary effects. Lahsasni et al. (4) studied moisture equilibrium data for the adsorption and desorption of water from prickly pear peel, in the temperature range of 30~50°C, which were found to have water activities ranging from 0.05 to 0.9. The results show that the equilibrium moisture content increases, with decreasing temperature at a constant relative humidity, with desorption and adsorption curves of prickly pear peel showing similar rates.

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Effects of drying on water activity and moisture

The drying process is one of the most important processes in the food industry. In most industrial processes there is at least one drying step, which means the removal of relatively small amounts of water can reduce the content of residual liquid to acceptably low values. Simultaneous heat and mass transfers occur during such processes, and different mechanisms of moisture transport and shrinkage within solid materials are some of problems associated with the drying of foods (5).

Lozano et al. (6) developed two generalized correlations for the prediction of water losses, based on the bulk shrinkage coefficients for fruit and vegetables. Ratti (7) proposed that the shrinkage characteristics of potatoes, apples and carrots were not only a function of the moisture content, but also depended on the operation conditions and sample geometry. Madamba et al. (8) found that shrinkage of garlic during drying was fiber oriented, and differed from the reported isotropic shrinkage of fruits and vegetables. Sjoholm and Gekas (9) found the volume change of apples upon drying was linearly correlated with the water content. McMinn and Magee (10) reported a linear correlation for the shrinkage of cylindrical potato sample during drying in a tunnel dryer, with the moisture content and air temperature. Zhou et al. (11) reported a linear relation for the axial contraction and volume changes of cylindrical carrots during the drying in a fluidized bed with energy carriers. Hatamipour and Mowla (5) studied the shrinkage of carrots during drying in an inert medium fluidized bed.

It must be noted that air humidity has a decisive influence on the rate of drying, that is, on the velocity at which water leaves the solid matrix. If it is initially relatively high, it may provoke the so called "case hardening", that is the hardening of the outer surface, which in turn reduces the further rate of drying, and consequently, the volume reduction. Conversely, soft drying leads to a lighter deformation. In general, the whole cellular structure behaves differently, according to the velocity at which water leaves the cells.

COLOR

Color also plays an important role in the assessment of product quality and can inform us about many other properties, such as the ripeness of fruits and vegetables, product alterations and so on. The human color perception is made up of three attributes: hue (i.e., red, green, blue, etc.), saturation, or intensity, of the color (i.e., pastel, deep, medium, etc.) and lightness, or clarity (12).

Physical properties of color

The color of food is not a physical characteristic in the same sense as the boiling point, particle porosity, density and so on but rather one portion of the input signals to the human perception of appearance. Appearance may be influenced by a number of physical attributes of a food, as well as a series of psychological perceptions. It is possible to define color in a purely physical sense, in terms of the physical attributes of the food, but this approach has serious limitations when we trying to use color measurements as a quality control tool for food processing and merchandising.

Color can be defined in a physical sense as the energy distribution of the light reflected by, or transmitted through, a particular food. Energy may be described as a continuous electromagnetic spectrum ranging from gamma rays, with wavelengths in the region of 10^{-5} nm, to wavelengths around 10^{17} nm, for power transmission. The portion of the electromagnetic spectrum to which the eye is sensitive (380~770 nm) is an exceedingly small portion of the total. From a chemical point of view, humans are accustomed to thinking of energy absorption in the ultraviolet (100~380 nm) and the infrared (770~1,000,000 nm) as well as the visible. Obviously, it is only energy absorption in the visible range that contributes to the perception of color (13).

Effect of thermal processing on color

The most common change that occurs during thermal processing of green spice-vegetables is the conversion of chlorophylls to pheophytins, causing a change from bright green to olive-brown. Chlorophyll degradation involves the loss of phytol, to form chlorophyllide, with the loss of Mg^{2+} to form pheophytin, for the conversion of phytol to from pheophorbide and with the additional loss of carbomethoxy groups to form pyropheophytin. The degradations of both chlorophyll and color during thermal processing follow first-order reaction kinetics. Ahmed et al. (14) found that the color degradation during thermal processing of chilli puree followed first-order reaction kinetics. An increase in the green color of the chilli puree was observed with increasing fineness as was reflected by the Hunter color 'a' value (Table 1). The L, a, and b values, and different combinations of these, were selected to ascertain their effect on the total color change of chilli puree. The reaction rate constants for selected combinations of these color parameters for green chilli puree are summarized in Table 2.

Effect of freezing on color

Freezing is an excellent method of the long-term preservation of food products, and has gained widespread attention. Food can be reliably protected against invading microorganisms by freezing below -10°C, or in extreme cases to -12°C, and the activities of the native enzymes

Table 1. Rheological and Hunter color values of green chilli pureed through selected screens (14)

Mesh No.	Screen opening (mm)	Bostwick consistency (cm)	Consistency index, K ($Pa.s^n$)	Flow behavior index, n (-)	Apparent viscosity, η, at 100 rpm ($Pa.s^n$)	Hunter color value		
						L	a	b
10	1.68	1.0	56.69	0.081	1.72	28.97	-5.41	13.96
12	1.41	1.4	52.60	0.084	1.57	29.16	-5.49	14.26
14	1.19	2.0	41.80	0.091	1.51	29.30	-5.67	14.30

Table 2. Reaction rate constants for selected combinations of color parameters for green chilli puree at 60°C (14)

Sample No.	Combination	*k* (per min)	R^2	Standard error
1	L	0.032	0.943	0.0002
2	-a	0.041	0.963	0.0021
3	b	0.045	0.779	0.0009
4	-La	0.044	0.971	0.0020
5	-L/a	0.038	0.951	0.0022
6	L/b	0.001	0.348	0.0008
7	Lb	0.008	0.873	0.0010
8	-ab	0.046	0.989	0.0013
9	-a/b	0.036	0.901	0.0030
10	-Lab	0.049	0.992	0.0012
11	-La/b	0.039	0.923	0.0029
12	-L/ab	0.042	0.986	0.0014
13	-bL/a	0.033	0.870	0.0030

in common foods are substantially reduced by bringing the temperature down to below the approximately range of -18 to -30°C. The residual activities of enzymes are then quite easily inhibited by suitable supplementary treatments (15). In recent years, increased ownership of domestic freezers and microwave ovens has boosted rapid increases in sales of frozen food. Current challenges lie on the production efficiency and high product quality.

Color loss during frozen storage is attributed to the fading of the vivid green color of the chlorophyll to an olive brown, characteristic of pheophytin. This phenomenon is known as pheophytisation, where the center magnesium is replaced by hydrogen. Another common type of deterioration is the removal of the phytol chain, leading to the formation of chlorophyllide (removal from chlorophyll) or pheophorbide (removal from pheophytin). Furthermore, reactions related with the functional side groups of chlorophyll form colorless products, which also affect color during frozen storage (e.g., the isocyclic ring may be oxidized to form allomerised chlorophyll). Because pheophtisation reaction rates are generally higher than other chlorophyll degradation pathways, it is considered the most important mechanism of chlorophyll destruction during food processing (16).

RHEOLOGICAL PROPERTIES

The rheological properties of food materials are also very valuable, and useful in food processing, handling and storage (17). Rheological characteristics influence heat transfer, transfer of mass, mixing and sedimentation in fluid foods. In some instances, the fluid consistency may be altered by the high shear rates encountered in these processes. Types of rheological behavior include: Newtonian behavior (Fluids that exhibit a linear relationship between shear stress and shear rate passing through the origin are called Newtonian; e.g., Food materials such as dilute aqueous solutions, milk, and vegetable oils) and Non-Newtonian behavior (Their shear-stress vs. shear-rate plots are either not linear, or do not go through the origin, or both).

The relationship between shear stress and shear rate of the Non-Newtonian materials is most commonly described by a two-parameter power law model, of the form:

$$T_{yx} = -K\ (dx/dy)$$

where,

K = consistency coefficient ($N \cdot s/m^2$)
n = flow behavior index (dimensionless)

If $n < 1$, the material is called a pseudoplastic or shear-thinning fluid; $n > 1$, then it is dilatant or shear thickening; $n = 1$, Newtonian.

Rheological properties of gelatinized starch dispersions

During heat treatment in heat exchangers, a very significant change in the apparent viscosity of starch dispersions has been observed. This generates significant changes in the velocity profiles, which, in turn, considerably modifies the temperature profiles and pressure drops inside the process equipment. In order to control the final rheological properties of starch-based food products, it is necessary to have a better knowledge of the influence of the temperature and shear rate, and their coupled effects, on the rheological behavior of starch dispersions for each step of a manufacture process.

Several works have shown that the flow behavior index drastically changes during gelatinization. Starch behavior changes from Newtonian, before swelling, to dilatant, during the early stages of gelatinization, and later becomes shear-thinning at the end. With regard to the consistency index evolution with temperature at each stage of gelatinization, it is not entirely justified to compare the consistency indices between stages as their units (Pa · s^n) are functions of the flow behavior index, and it is even less justified to obtain a correlation as a function of the temperature (18).

Rheological behavior of dairy products

Knowledge of the rheological properties of dairy products is essential for materials handling and the design and operation of the processing equipment used in the dairy industry. Certain dairy products, when subjected to deformation, exhibit yield and work softening, apparently due to structural breakdown. However, the structure may be rebuilt with time, when the product is allowed to set, and exhibit a thixotropic behavior (thickening), a characteristic of many food products (19).

The rheology of dairy products has been studied to a limited extent. Under certain conditions (e.g., moderate shear rate, fat contents below 40% and at temperatures above 40°C, at which the fat is liquid and no cold agglutination occurs) milk, skimmed milk and cream are, in effect, fluids, with Newtonian rheological properties. Raw milk and creams exhibit Non-Newtonian rheological properties when they are held under conditions that allow cold agglutination of the fat globules (below 40°C and low shear rates) (20). Sweetened-condensed milk, cream and yogurt show thixotropic (shear-thinning) behavior, i.e., their apparent viscosities are inversely related to shear rates. Penna et al. (21) studied the rheological characteristics of five different commercial brands of lactic beverages (A: Nestlé, B: Danone, C: Batavo, D: Parmalat and E: Vigor). The main characteristic of the relationship shear stress/shear rate was the development of a hysteresis curve; the higher the area below the curve, the higher the thixotropic effect (22). The rheograms showed that samples behave as a Non-Newtonian fluid, pseudoplastic type, with the presence of thixotropy as a result of structural breakdown. Fig. 1 and 2 show the shear stress/shear rate relationship curves for the lactic beverage samples, A and E obtained at 5 and 25°C, respectively.

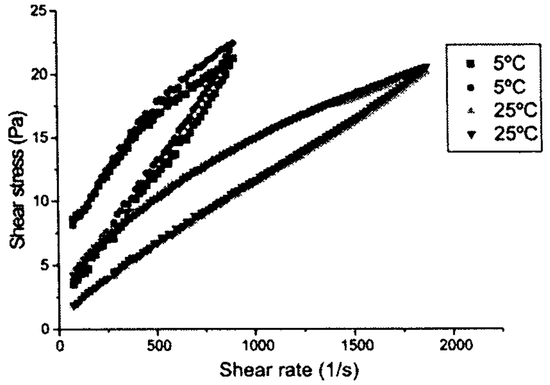

Fig. 1. Shear stress vs. shear rate relationship curves for lactic beverage A (Nestlé), at 5 and 25°C (21).

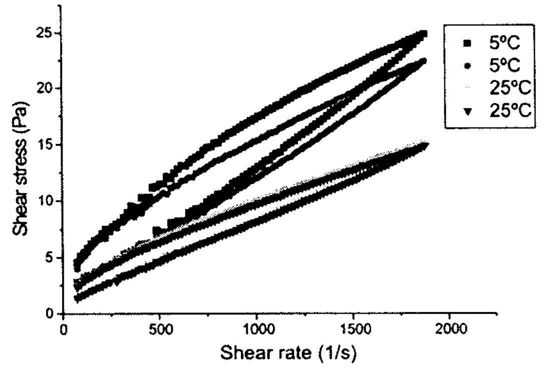

Fig. 2. Shear stress vs. shear rate relationship curves for lactic beverage E (Vigor), at 5 and 25°C (21).

Effect of temperature on polymer rheology

Many chemical and other industries utilize Non-Newtonian fluids in their processes (23). One of the most important characteristics is the effect of the shear rate on the fluid viscosity. In some cases, the presence of small quantities of polymers produces important effects on the behavior of the liquid phase. Non-Newtonian polymers are present in industries, such as the food, textile, pharmaceutical, cosmetics and so on (24). For example, some polymers are used as additives to contribute to the texture or to stabilize some industrial products. In the last few decades, polymers have been introduced in the biotechnology industry, due to their ability to form gels with cations, and have been used as immobilization materials for living cells (25). Industrially manufactured products contain additives to optimize their flow behaviors. This is also valid for the food industry where, the selection of the best additive must be made employing rheological parameters as criteria (26).

The consistency coefficient (K) and flow behavior index (n) are typical rheological parameters used in the power-law model. The consistency coefficient K is a strong function of both the concentration of a solution and its temperature, whereas n does not have a strong dependence on the concentration and temperature of the polymeric solution (27). The effect of temperature on the rheological behavior of the polymers solutions has been studied by Gómez-Diaz and Navaza (26). Their experimental results show that the solutions have more Newtonian behavior (flow behavior index n increase) when the temperature is higher, which exhibited a linear trend. The polymer concentration of the solution has no influence on the slope of the plot. In relation to the consistency coefficient (K), the temperature caused decreases in its value, which also showed a linear trend. The slope is larger when the concentration of the polymer was increased (Fig. 3～6) (26).

Effect of storage on rheological characteristics

The effects of storage of frozen parotta dough (FPD), and ready-to-bake frozen parotta dough (R-FPD) at -20°C for 3 months, on the rheological characteristics were studied by Indrani et al. (28). The results (Table 3) indicated a decrease in the farinograph peak consistency, from 510 to 470 BU, the extensograph resistance to extension, from 230 to 200 BU, and an increase in the extensibility, from 155 to 170 mm, due to the storage of FPD for up to 3 months at -20°C. Inoue et al. (29) reported that the maximum resistance decreased, and the dough extensibility increased significantly, after the frozen storage of yeasted dough for 70 days. Unlike yeast-raised products, no significant change was observed in the strength of the FPD.

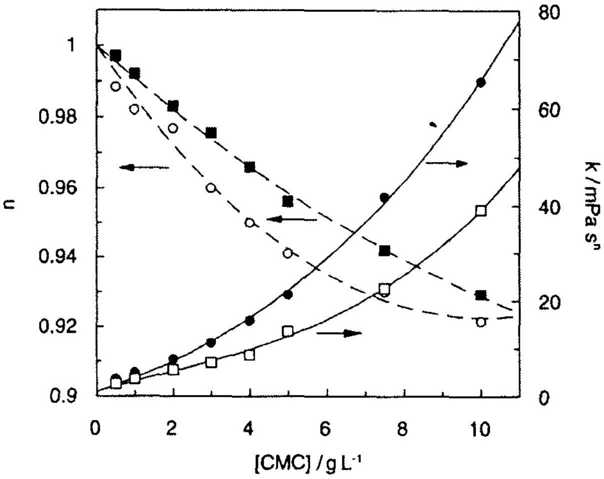

Fig. 3. Influence of the CMC concentration on the rheological parameters, n -25°C (○) and 40°C (■) and k -25°C (●) and 40°C (□) (26).

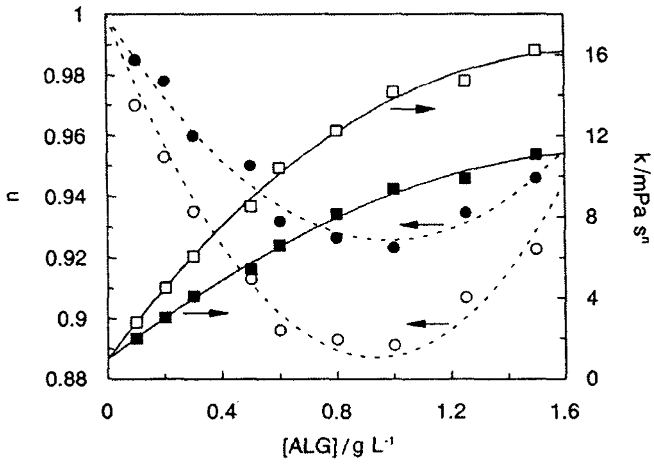

Fig. 4. Influence of the alginate concentration on the rheological parameters, n -25°C (□) and 40°C (■) and k -25°C (○) and 40°C (●) (26).

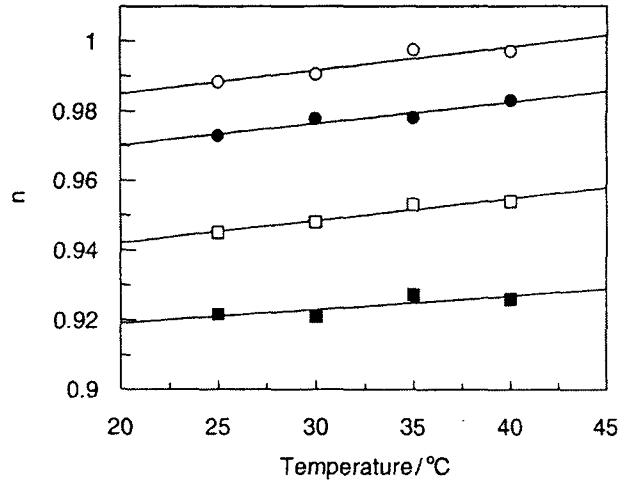

Fig. 5. Influence of temperature on behavior index of the CMC, n: 0.5 gl-1 (○), 2.0 gl-1 (●), 5.0 gl-1 (□) and 10.0 gl-1 (■) (26).

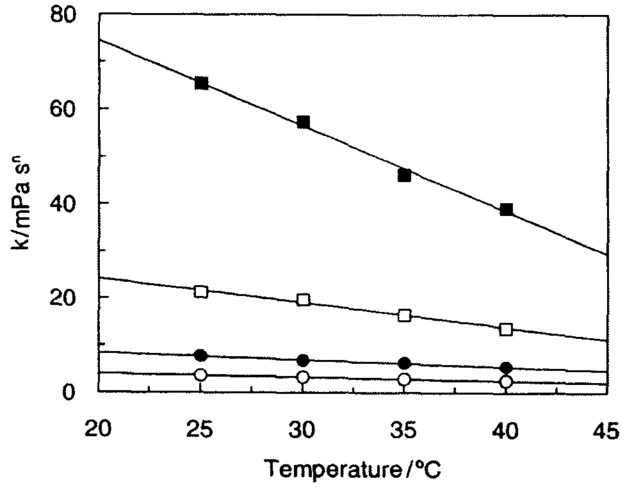

Fig. 6. Influence of temperature on consistency index of the CMC, k: 0.5 gl-1 (○), 2.0 gl-1 (●), 5.0 gl-1 (□) and 10.0 gl-1 (■) (26).

Table 3. Effect of storage on the farinograph and extensograph characteristics of stored frozen parotta dough (28)

	Storage time (months)			
	0	1	2	3
Farinograph characteristics				
Peak consistency (BU)	510	510	500	470
Extensograph characteristics				
Resistance to extension, *R* (BU)	230	220	210	200
Extensibility, *E* (mm)	155	160	165	170
Ratio figure, *R*/*E*	1.48	1.38	1.27	1.23

Inoue and Bushuk (30), with extensograph measurements compared yeasted and non-yeasted frozen dough, and found that the gluten structure of the yeasted doughs was more vulnerable to the detrimental effects of freezing than the non-yeasted doughs. Hence, parotta dough, being non-yeasted dough, showed negligible changes in its rheological properties during frozen storage. In the case of yeasted doughs, the dough stability and strength both decreased, due to the increase in reducing substances leached from the yeast, which caused a reduction in the gluten proteins (28). Autio and Sinda (31) concluded, from viscoelastic measurements, that there was a loss of polymer cross-linking in frozen and thawed doughs, which led to a weakening of the gluten network.

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