Relationship between Physical and Hydration Properties of Soluble and Insoluble Fiber of Artichoke

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Hot water and cellulase hydrolysis extraction methods were used to obtain soluble and insoluble fractions of dietary fiber (DF). Concentrates of the DF fractions were used to study their structure, physical properties (particle size, density, porosity, and oil adsorption capacity), hydration properties (swelling, water binding capacity, and viscosity), and glucose dialysis retardation index. Hydrolysis with cellulase modified the physical and hydration properties of the different samples analyzed, since this enzyme reduced the particle size in soluble and insoluble dietary fiber (SDF and IDF, respectively), while increasing the water binding capacity of IDF and decreasing that of SDF. Correlation studies carried out between the different properties analysed, showed that the behavior of hydrated fiber and the delay in glucose diffusion are determined by the physical properties of fiber.

Keywords: *Dietary fiber; functional properties; fiber extraction and artichoke*

INTRODUCTION

The study of dietary fiber (DF) should not be confined to a knowledge of the amount of DF in foods, nor to a knowledge of its percentage in a diet. The main interest of studies into DF is to understand the physiological effects that it may have for the human organism. These aspects have been widely reviewed by different authors (Reiser, 1984; Schneeman, 1987; Topping, 1991; Periago *et al.*, 1993). The functional properties of DF are involved in the biological effects. These are a combination of the rheological, colligative, and surface properties of their components (Eastwood and Morris, 1992). The soluble and insoluble components of DF behave differently, according to whether they are hydrated, swollen, or attacked by enzymes, such behavior being reflected in their structure and physical characteristics. Although insoluble and soluble DF have different effects and intensities of effect on the human organism, this statement may not be completely true in global terms, since both fractions have some components, such as uronic acids, that have the same action: the reduction of postprandial blood glucose level concentrations (Wolever, 1990). For this reason, the functional properties of DF from different sources should be studied in order to obtain from the individual characteristics of each one a more global and accurate vision of their behavior in the human organism.

The artichoke is a plant of the Compositae family rich in DF and is characterized by the absence of starch as polysaccharide reserve (Belitz and Grosch, 1985). Especially the artichoke heart is a good source of insoluble dietary fiber (18.11%) and soluble dietary fiber (26.74%) (Lintas and Capelloni, 1988), which makes it possible to obtain concentrates of both fractions with a high yield.

The purposes of the present work were to study the physical structures and functional properties of concentrates of DF fractions of artichoke, and to evaluate their potential hypoglycemic effects by using an "in vitro" method. The concentrates of DF from artichoke were obtained by a simple method (hot water) and a second method involving the modification of the physical characteristics of DF. These modifications were obtained by using cellulase, which effects cell wall by disrupting the link $\beta(1-4)$ between glucose molecules present in cellulose and hemicelluloses.

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EXPERIMENTAL PROCEDURES

Materials. Artichoke hearts (*Cynara scolymus* L.) were provided by HERO SPAIN, S. A. (Murcia, Spain). The samples were freeze-dried in a Virtis Freeze-Dried, Model Bench Top 3 (Virtis Co., Gardiner, NY) and ground to obtain a powder, which was then passed through a 40 mesh sieve size screen and placed in glass jars with a packet of desiccant and stored in a still-air freezer at −40 °C until used for analysis. The artichoke flour was used to obtain both fractions of DF (soluble and insoluble) following two procedures.

Extraction and Determination of Dietary Fiber. Prior to obtaining the artichoke DF fractions, the total, soluble and insoluble DF content were determined in artichoke flour by the enzymatic-gravimetric method of Prosky *et al.* (1988). Two methods were used to obtain the fractions of DF: (I) extraction in hot water (90 °C) at pH 7.5 for 90 min, and (II) hydrolysis with cellulase of *Trichoderma viridae* (Boehringer Mannheim GmbH 238104) in phosphate buffer 0.05M (pH 6.5) at 60 °C for 4 h. In both methods, the separation between water-soluble and water-insoluble fractions was performed by filtration using crucibles p#2 (40−90 μm). The insoluble fractions obtained in hot water (WIF) and hydrolyzed with cellulase (CIF) were recovered, and the soluble fractions (WSF and CSF, obtained in hot water and hydrolyzed with cellulase, respectively) were precipitated with 96% ethanol and recovered by centrifugation (9500*g*) for 30 min. The residues of the soluble and insoluble DF obtained by the two methods were freeze-dried and placed in glass jars with a packet of desiccant and stored in a still-air freezer at −40 °C until used for analysis.

The physical properties, hydration properties, and glucose dialysis retardation index (GDRI) were evaluated in artichoke flour, WIF, WSF, CIF, CSF, and guar gum (Sigma, A6549), which was used as a reference.

Scanning Electron Microscopy. The freeze-dried samples were coated with a thin layer of gold in a vacuum evaporator

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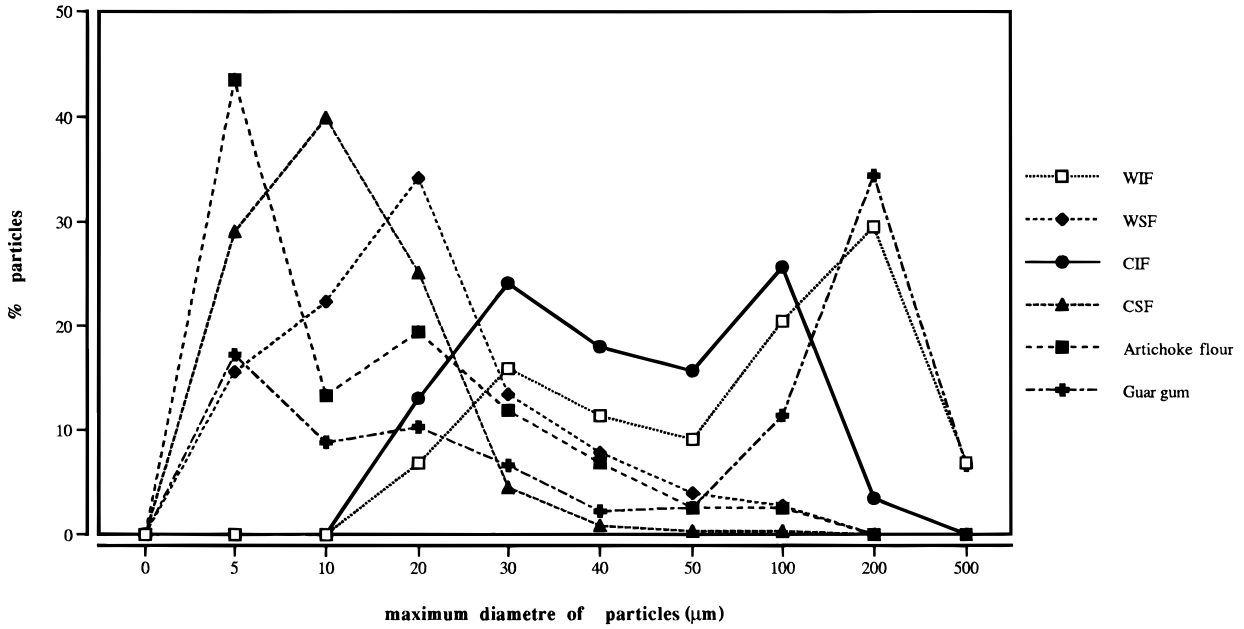

Figure 1. Particle size distribution as a function of linear size for the different samples analyzed.

(Bio-Rad Ducaron Division), and the structure and morphology of fiber were observed in a JEOL 6100 scanning electron microscope at an accelerating voltage of 15 kV.

Analysis of Physical Properties. *Particle Size.* Particle size distribution was measured by studying the images obtained by scanning electron microscopy (SEM) JEOL 6100 at an accelerating voltage of 15 kV and at 55×. Four fields per sample were studied to obtain a representative number of particles (between 300 and 800 particles). These images were processed using the MIP system (Microm Image Processing; Microm, Spain), supplied in the system IMCO 10 Kontron Bildanalyse (IMCO 10 Image Computer, Germany). A video camera with a macrooptic adaptation was used to capture the images. After digitalizing the image, the system was calibrated to convert the number of pixels into microns (μm) taking as reference the zone calibrated in each SEM image. Particle size was expressed as a function of maximum diameter (linear size). The problem caused by particle depth was solved by adjusting the gray level to obtain optimum resolution at the image. When each particle had been outlined, the image was then inverted, making black pixels white and white pixels black, because the analyzer only measures black objects.

Density. Direct density (ρ_d) and bulk density (ρ_b) were determined according to the methods described by Parrott and Thrall (1978). Direct determination of density involved the addition of the sample to a specific mark on a calibrated graduated cylinder with minimal shaking to assure complete filling. The contents of the cylinder were then weighed and the results expressed as grams per milliliter. The bulk density measurement utilized a calibrated graduated cylinder with an embolus. The graduated cylinder was filled with a known amount of sample. Pressure was applied manually until contents were packed tightly and additional pressure would not further reduce the volume. The volumetric measure was then read and the results were expressed as grams per milliliter.

Porosity. Fiber porosity was determined by using the calculatation of specific volume that could be used as a index of the capillary structure differences (Chen *et al.*, 1984; Cadden, 1987). An amount of sample, which varied by particle size and density of each sample, was deposited into a glass cylinder, previously filled with a known volume of water. The specific volume was determined by measuring the volume of water displaced by a known weight of dry fiber.

The oil adsorption capacity was determined by the procedure reported by Sosulski *et al.* (1976).

Analysis of Hydration Properties. *Swelling capacity* (SWC) was measured according to the procedure described by Auffret *et al.* (1994).

Water binding capacity (WBC) was determined according to the method described by Sosulski *et al.* (1976), although some modifications were made. Samples (300 mg) were weighed and left to stand for 1 h in distilled water (10 mL) at room temperature (23 °C) before being were centrifuged for 20 min at 14000*g*. The residues were left for 30 min, dried overnight at 110 °C, and weighed. The SWC and WBC measurements were made using distilled water and 0.15 mol/L NaCl, as described by Guillon *et al.* (1992) and Auffret *et al.* (1994).

The viscosity of each fiber suspension was determined using a rotational viscometer LV8 (U.K. Ltd., England) at 37 °C on a 2% (w/v) fiber suspension, and with shear rates of 1.83 s^{-1} for guar gum and 73.42 s^{-1} for the other solutions.

The glucose dialysis retardation index (GDRI) was measured according to the procedure reported by Adiomtore *et al.* (1990).

Statistical Analysis. All determinations were carried out at least three times. Differences between different fiber types were tested using ANOVA (SAS, 1985). When a statistically significant effect was obtained, a Duncan's multiple range test was realized. Principal component analysis (PCA) was performed using the PRINCOMP procedure (SAS, 1985) in order to summarize data. Information about physical property set/hydration property set/glucose dialysis retardation index was obtained through canonical correlation analysis (CCA), using the CANCORR procedure (SAS, 1985). The purpose of CCA is to explain the relationship between two sets of variables.

RESULTS AND DISCUSSION

Physical Properties. The distribution of particle sizes is shown in Figure 1 as a function of maximum diameter (linear size). Artichoke flour showed the smallest particle size (76.26% were smaller than 20 μm, Figure 1) and guar gum had the largest. Among the other samples, the insoluble fractions (WIF and CIF) had a particle size greater than the soluble fractions (WSF and CSF), which had a high percentage of particles smaller than 20 μm of linear size (72.09 and 94.73% in WSF and CSF, respectively). The effect of cellulase on particle size distribution in the soluble and insoluble fractions is clear, the resulting particles being smaller than those obtained by the water extraction method.

Density and Porosity. As shown in Table 1, the highest values of the direct determination of density (ρ_d) and bulk density (ρ_b) were obtained for guar gum and artichoke flour (0.57 and 0.42 g/mL for ρ_d, and 0.73 and

Table 1. Physical Property Results Obtained for Different Samples Analyzed (Mean ± SD)[a−e]

sample	ρ_d (g/mL)	ρ_b (g/mL)	specific volume (cm^3/g)	OAC (g/g)
WIF	0.079 ± 0.001^d	0.35 ± 0.01^d	$0.88 \pm 0.03^{b,c}$	5.68 ± 0.24^a
WSF	0.379 ± 0.015^b	0.51 ± 0.02^c	1.14 ± 0.05^a	2.13 ± 0.01^b
CIF	0.154 ± 0.003^c	0.45 ± 0.02^c	0.74 ± 0.06^c	5.81 ± 0.08^a
CSF	0.378 ± 0.011^b	0.59 ± 0.05^b	1.05 ± 0.01^a	$1.79 \pm 0.06^{b,c}$
artichoke flour	0.423 ± 0.025^b	0.74 ± 0.01^a	0.89 ± 0.09^b	1.31 ± 0.01^c
guar gum	0.570 ± 0.018^a	0.73 ± 0.03^a	ND	1.26 ± 0.08^c

[a−d] Means within the same column with different superscript letters $a-d$ were significant at $p < 0.05$. [e] Abbreviations: ρ_d, direct density; ρ_b, bulk density; OAC, oil absorption capacity; WIF, insoluble fraction obtained in water; WSF, soluble fraction obtained in water; CIF, insoluble fraction obtained with cellulase hydrolysis; CSF, soluble fraction obtained with cellulase hydrolysis.

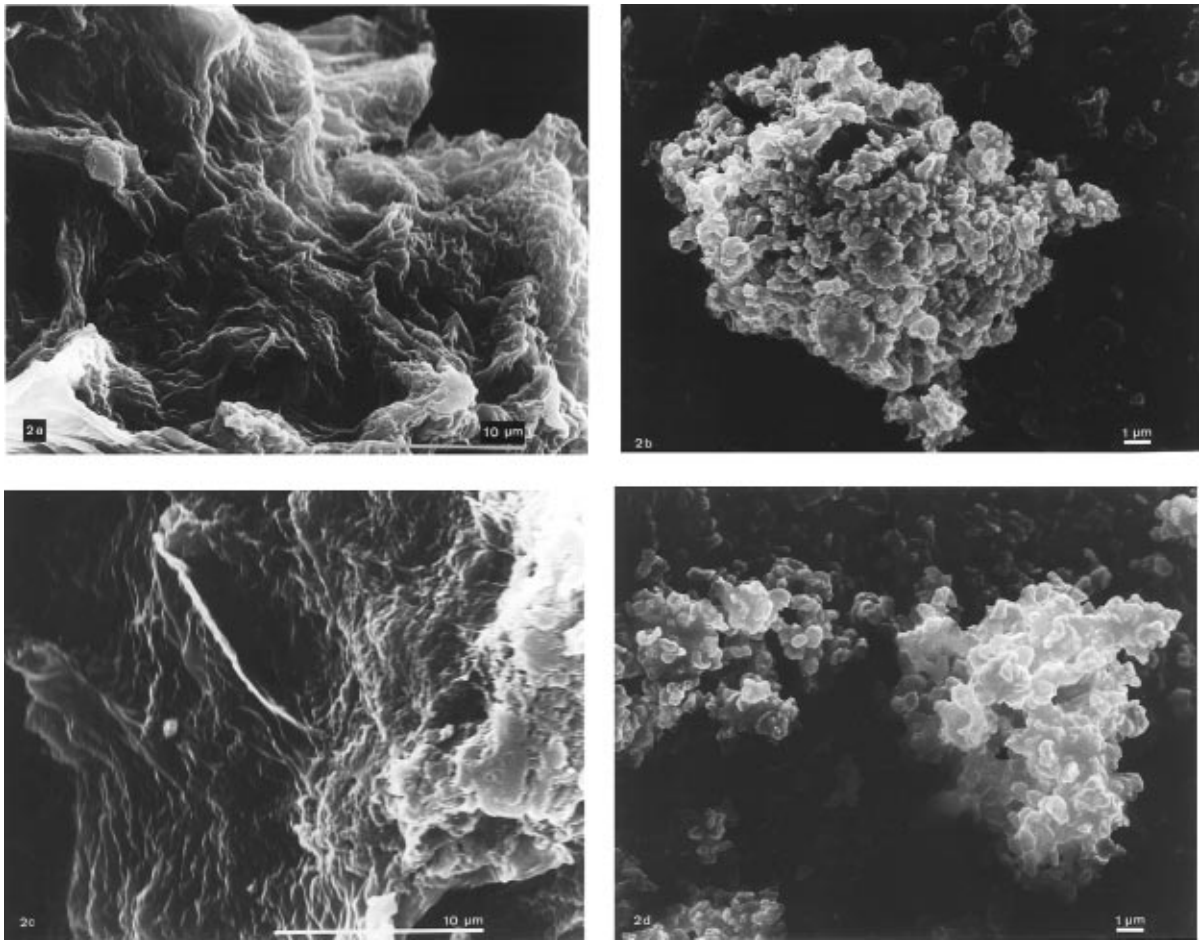

Figure 2. Scanning electron micrographs of insoluble (WIF) and soluble particle obtained in hot water (WSF) (parts a and b, respectively), and insoluble (CIF) and soluble particle obtained with a cellular hydrolysis (CSF) (parts c and d, respectively). Magnification 2500× for WIF, 3500× for CIF and 4500× for WSF and CSF. (Reproduced at 30% of original size.)

0.74 g/mL for ρ_b, respectively). The smallest values obtained were for the insoluble fractions (WIF and CIF) with 0.079 and 0.154 g/mL for ρ_d, and 0.35 and 0.45 g/mL for ρ_b, respectively. The WSF and CSF values were between those of artichoke flour and the insoluble fractions (0.379 and 0.378 g/mL for ρ_d, and 0.51 and 0.59 g/mL for ρ_b, respectively).

Table 1 also depicts the *specific volume* and oil adsortpion capacity (OAC). The specific volume of the soluble fractions was significantly different ($p < 0.05$) from than that of the insoluble. The higher specific volumes of WSF and CSF show that these fractions have a more porous surface than the insoluble fractions (WIF and CIF). This fact was also observed in the study of particle structure in every sample analyzed by SEM. The surface of WSF (Figure 2b) and CSF particles (Figure 2d) shows a capillary structure and a more regular morphology than the WIF and CIF particles (Figure 2, parts a and c, respectively), in which a porous surface cannot be seen. The specific volume of soluble and insoluble fractions was reduced by cellulose hydrolysis, because the enzyme disrupts the chains of polysaccharides on linked $\beta(1-4)$ between two glucose molecules, causing a reduction of particles size. A similar effect on specific volume was described by Cadden (1987) in wheat bran when his samples were ground to obtain a reduction of particle size.

The oil adsorption capacity (OAC) is related to the nature of the surface and the density or thickness of particles, so that those particles with the greatest surface area theoretically present a greater capacity to adsorb and bind components of an oily nature (Amadò, 1984). Sosulski and Cadden (1982) in studying different sources of DF found that lignin-rich samples had more OAC. In our study, the insoluble fractions had higher OAC levels than the soluble fractions, due to their high percentage of particles with a large size (Figure 1), and for the lignin to be found in their chemical composition (a component only measured in the insoluble fiber). However, Fleury and Lahaye (1991) in a seaweed (*Laminaria digitata*) found that this property increased with smaller particle size, although it could be affected

Table 2. Hydration Property Results Obtained for Different Samples Analyzed (Mean ± SD)[a−g]

sample	SWC (g/g)		WBC (g/g)		viscosity (mPa)
	H_2O	NaCl (0.15 mM)	H_2O	NaCl (0.15 mM)	H_2O
WIF	30.26 ± 0.32^{b}	$19.68 \pm 0.31^{b,e}$	5.76 ± 0.61^{c}	5.98 ± 0.84^{c}	$1.292 \pm 0.020^{b,e}$
WSF	$8.00 \pm 0.03^{d,f}$	7.82 ± 0.03^{d}	10.97 ± 0.04^{b}	10.55 ± 0.05^{b}	1.035 ± 0.025^{b}
CIF	20.07 ± 1.10^{c}	$18.00 \pm 0.11^{b,f}$	10.74 ± 0.06^{b}	10.14 ± 0.05^{b}	1.185 ± 0.005^{b}
CSF	9.72 ± 0.04^{d}	8.60 ± 0.02^{d}	2.83 ± 0.43^{d}	2.54 ± 0.19^{d}	$0.995 \pm 0.015^{b,f}$
artichoke flour	$10.98 \pm 0.71^{d,e}$	12.54 ± 0.55^{c}	5.24 ± 0.15^{c}	5.20 ± 0.05^{c}	1.050 ± 0.040^{b}
guar gum	84.02 ± 2.25^{a}	89.30 ± 1.07^{a}	17.72 ± 0.05^{a}	17.65 ± 0.18^{a}	210.560 ± 0.240^{a}

[a−f] Means within the same column with different superscript letters $a-d$ were significant at $p < 0.01$ and e, f were significant at $p < 0.05$. [g] Abbreviations: SWC, swelling capacity; WBC, water binding capacity; WIF, insoluble fraction obtained in water; WSF, soluble fraction obtained in water; CIF, insoluble fraction obtained with cellulase hydrolysis; CSF, soluble fraction obtained with cellulase hydrolysis.

by the charge density and hydrophilic nature of individual particles. The cellulose does not change the OAC, neither the soluble nor insoluble fractions as shown Table 1. The other samples, artichoke flour and guar gum, gave the lowest values (around 1 g/g) showing no significant differences ($p < 0.05$) with CSF.

Hydration Properties. Table 2 shows the hydration properties of each DF fraction obtained by extraction with hot water or by hydrolysis with cellulase. Their properties were compared with the hydration properties of artichoke flour and guar gum. *Swelling capacity* (SWC) and *water binding capacity* (WBC) were determined using deionized water and a solution of 0.15 mol/L NaCl.

The highest SWC value (30.26 g/g) corresponded to WIF in deionized water, while the lowest value was obtained for WSF in NaCl (7.82 g/g). Cellulase hydrolysis significantly reduced the SWC of the insoluble fractions, while this effect was not noticeable for soluble fractions. SWC determined in deionized water was higher than that determined in NaCl for WSF, CSF, WIF, and CIF, and higher in NaCl for artichoke flour and guar gum. With the excepcion of the WBC value of guar gum (which was taken as a reference), the highest values were obtained for WSF (10.97 g/g). However, cellulase hydrolysis changes the WBC of the soluble and insoluble fractions of the DF solution, lowering it from 10.97 g/g (WSF in deionized water) to 2.83 g/g (CSF in deionized water), and increasing it from 5.76 g/g (WIF in deionized water) to 10.74 g/g (CIF in deionized water). The WBC was only greater in NaCl than in deionized water in the case of WIF, while in the other samples WBC was always greater in deionized water than in NaCl.

SWC and WBC are two hydration properties which are determined by the content in water-soluble-fiber-components of foods (Sosulski and Cadden, 1982), and whose values should show a similar evolution. In addition to the chemical composition of fiber, some physical properties such as structure, particle size, porosity, and density are important to understand the different behavior of samples during hydration (Robertson and Eastwood, 1981; Auffret *et al.*, 1994). The fact that insoluble fractions showed a higher SWC than the soluble fractions could indicate that the structural characteristics play a more important role in the kinetics of water uptake in artichoke fiber than the chemical composition. However, it must also be considered that some components of IDF, such as hemicelluloses and lignin, have water affinity (Holloway and Greig, 1984).

A correlation study for SWC and WBC was showed a negative correlation for CIF ($r = -1.000$; $p < 0.05$) and positive correlations for WSF ($r = 1.000$; $p < 0.001$) and CSF ($r = 0.997$; $p < 0.05$). This study confirmed that the structural characteristics of the insoluble fractions had a determining function in water uptake kinetics. The modifications of the physical structure of samples caused by cellulase resulted in a negative correlation index, and indicate that when insoluble fractions are hydrolyzed by cellulase, the modification in physical properties does not affect both hydration properties in the same way, while in soluble fractions SWC and WBC evolve in a similar way. These facts could help us understand why the WBC of our samples were lower than SWC. DF may interact with water through two mechanisms, mainly (1) water held in capillary structures as a result of surface tension strength and (2) water interacting with molecular components of food through hydrogen bonding or dipole forms (Chen *et al.*, 1984). SWC of fibers represents the volume of hydrated fiber under gravity forces, while WBC represents the volume of hydrated fiber measured under centrifugal forces (Auffret *et al.*, 1994). On the basis of the results shown in Table 2, we may assume that the physical properties of the fiber related to fiber structure have an important effect on the insoluble fractions hydration of artichoke, having a higher swelling than soluble fractions. However, in the measurement of WBC the fraction of water that interacts with molecular components of food will be determined, removing the water bound weakly to fiber (mainly as a result of the fiber surface structure through surface tension strength). Therefore, chemical composition is the main factor that determines water uptake for WBC, showing WSF higher values than WIF.

It is important to emphasize the effect of cellulase on the hydration properties. In insoluble fiber the cellulase caused a reduction of SWC (from 30.26 to 20.07 g/g) only in the sample solubilized in deionized water. However, the cellulase inverted the WBC of insoluble and soluble fibers, since this property was greater in CIF than in CSF.

The increase of insoluble fiber WBC might be due to the reduction of particle size, and thus an increase in the total surface area that interacts with water molecules. This process was also explained by Auffret *et al.* (1994) in samples with a cell wall rich in cellulose. But for the soluble fraction, with a particle size smaller than that of the insoluble fractions, the decrease of WBC after cellulase hydrolysis may be explained by some modifications in soluble hemicelluloses. These DF components, present in both fractions, are responsible for part of the fiber's hydrophobic characteristics, and a similar reduction has been observed in other sources of fiber (Heller *et al.*, 1977; Auffret *et al.*, 1994).

In general, SWC and WBC fell with the higher ionic strengths of the solubilization medium, except SWC of artichoke flour and guar gum, and WBC of WSF. A similar trend was observed by Parrott and Thrall (1978), Bertin *et al.* (1988), Fleury and Lahaye (1991), and Auffret *et al.* (1994). These authors explained that the presence of charged polysaccharides (uronic acids) in a medium with ions in solution could produce a screening of their charges, thus a reduction of the electrostatic

Table 3. Studies of Canonical Correlation between the Functional Properties and GDRI[a]

type of study	canonical correlation	significance grade	total redundance (%)	
physical vs hydration	0.983	*b*	physical 72.60	hydration 83.04
physical vs GDRI	0.902	*c*	physical 30.02	GDRI 73.47
hydration vs GDRI	0.748	NS[d]	hydration 37.13	GDRI 47.62

[a] Glucose dialysis retardation index. [b] Significant at $p < 0.001$. [c] Significant at $p < 0.05$. [d] NS, not significant at $p > 0.05$.

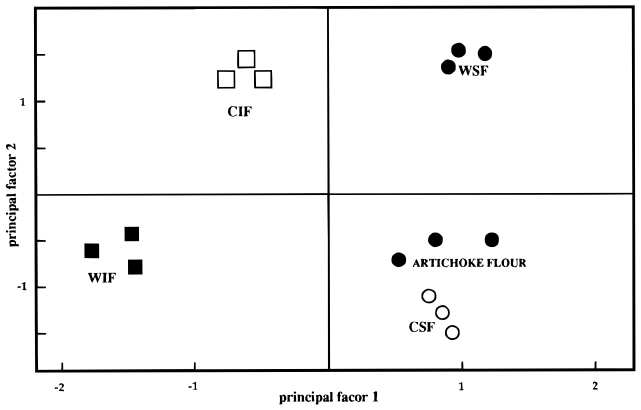

Figure 3. Distribution relative to different samples analyzed as function of two principal factors including all physical and hydration properties.

repulsion between polysaccharides, and thus decrease their affinity for water.

Viscosity. All the fiber suspensions showed very low viscosity values (Table 2) (ranging from 0.99 to 1.29 mPa) if compared with guar gum (210.56 mPa). Significant differences were found at $p < 0.05$ only between WIF and CSF, and no significant differences at $p < 0.01$ for any of the samples studied excluding guar gum.

The behavior of the hydration properties of DF is determined by particle structure and their size (Parrot and Thrall, 1978; Robertson and Eastwood, 1981; Sosulski and Cadden, 1982). A study of the canonical correlation among physical and hydration properties (Table 3) allows us to know the influence that density, specific volume, and OAC have on the hydration behavior of artichoke DF fractions. Such a study confirms the high significant correlation between the physical and hydration properties ($r = 0.983$; $p < 0.001$) and establishes that the hydration behavior of fibers may be explained by their physical properties. On the other hand, the high redundancy in both groups of properties (72.60 for physical and 83.04 for hydration), means that the total variability in both groups could be explained by a smaller number of variables in each group.

Figure 3 represents each fiber fraction as a function of two principal factor scores. Both explain 78.65% of total variance found, and give a general picture of the changes caused by the extraction method (water/cellulase hydrolysis) on the functional properties. This effect is observed through the distances obtained between WIF and CIF, and between WSF and CSF, respectively.

Glucose Dialysis. The glucose dialysis retardation index (GDRI) and the glucose concentrations of the dialysate are shown in Table 4. In all samples GDRI was greater after 30 than 60 min. None of the fiber solutions had a GDRI greater than the guar gum, whose index was 46.20% after 30 min of dialysis, close to the values reported by Adiotomre *et al.* (1990) (45.9%) and Gourgue *et al.* (1992) (44%).

Table 4. Effect of Fiber on Glucose Diffusion (Glucose Diffusion Retardation Index)[a] (Mean ± SD)

	30 min		60 min	
sample	glucose in dialysate (mmol/L)	GDRI (%)	glucose in dialysate (mmol/L)	GDRI (%)
WIF	1.17 ± 0.02	35.93	1.38 ± 0.11	28.49
WSF	1.41 ± 0.04	23.03	1.75 ± 0.02	9.59
CIF	1.22 ± 0.07	33.33	1.44 ± 0.07	25.57
CSF	1.34 ± 0.09	26.66	1.81 ± 0.04	6.24
artichoke flour	1.21 ± 0.01	33.43	1.36 ± 0.00	29.54
guar gum	0.98 ± 0.01	46.20	1.29 ± 0.04	33.32
control	1.83 ± 0.01	0	1.93 ± 0.08	0

[a] Glucose dialysis retardation index = 100 − [(fiber × 100)/control]. [b] Abbreviations: WIF, insoluble fraction obtained in water; WSF, soluble fraction obtained in water; CIF, insoluble fraction obtained with cellulase hydrolysis; CSF, soluble fraction obtained with cellulase hydrolysis.

At 60 min, the GDRIs of the insoluble fractions (WIF and CIF) and artichoke flour were greater than those of the soluble fractions (WSF and CSF), and close to the values shown by guar gum. GDRI is an useful *in vitro* method for the prediction of the effect of fiber on the delay in glucose adsorption in the gastrointestinal tract (Adiotomre *et al.*, 1990; Stevenson *et al.*, 1994). *In vivo* and *in vitro* studies of glucose absorption have shown that the delay in glucose adsorption in the gastrointestinal tract is determined mainly by the viscosity of soluble polysaccharides (Jenkins *et al.*, 1986; Adiotomre *et al.*, 1990). Our results did not show a trend similar to those obtained by these authors, since in our study the insoluble fractions had greater GDRI than the soluble fractions. This fact, together with the moderate effect in delaying glucose diffusion shown by WSF and CSF and their low viscosity compared with guar gum (Table 2), lead us to think that other factors are responsible, besides viscosity, for the delay in glucose diffusion. Similarly, the physical obstacle presented by fiber particles toward glucose molecules, and the entrapment of glucose within the network formed by the fibers, may explain why these samples had GDRI values closer to those observed in other sources of fibers with a high capacity of gelation, such as tragacanth gum with a 38.7% GDRI (Adiotomre *et al.*, 1990).

Steveson *et al.* (1994) described that a reduction in particle size and surface area produces changes in the rate of glucose liberation from polymers. The minor effect in the delay of glucose diffusion performed by the soluble samples in water could be explained in the same way, since their size was smaller than those of the insoluble samples in water. In artichoke flour this index was high at 30 and 60 min (33.43 and 29.54%, respectively), and close to the values obtained in guar gum after 60 min. In foods with SDF and IDF, both act simultaneously in delaying or blocking glucose molecules (Nishimune *et al.*, 1991). This fact could help explain the high values obtained with artichoke flour, especially if we note that in this sample both fiber fractions represent a high percentage (21.07 and 25.20% for IDF and SDF, respectively).

The relationship between both groups of functional properties and GDRI was established through a study of the canonical correlation and is shown in Table 3. There was no significant relation between the hydration variables and GDRI ($r = 0.748$; $p < 0.088$), but the physical properties were shown to be the determinant factors that control the delay of glucose diffusion by the artichoke DF ($r = 0.902$; $p < 0.05$). These results confirm that the action of artichoke DF and its fractions on the regulation of glucose absorption is mainly due

to their physical characteristics such as porosity and density, and show the ability to immobilize glucose within the interstices of the fiber particles. The effect of insoluble DF in the inhibition of glucose diffusion in the small intestine is considered by Nishimune *et al.* (1991) and may be due to the adsorption or inclusion of the smaller sugar molecules within the structure of the fiber particles. Other factors that have not been included in the statistical study, such as particle size or protein content, may have effects analogous to those described above (Eastwood and Morris, 1992). So, in addition to the effect of the fiber physical properties, the higher protein content of WIF and CIF (11.50 and 10.55%, respectively) than of WSF and CSF (1.09 and 1.00%, respectively) may have an influence on the higher values of GDRI obtained for insoluble fractions than for soluble fractions. However, glucose diffusion has been related to the soluble fiber content and viscosity of different sources of fiber (Adiotomre *et al.*, 1990; Wood *et al.*, 1990; Gourgue *et al.*, 1992), although it has not been observed for artichoke fiber in the present study.

We may conclude that the effect of artichoke DF and its fractions on glucose diffusion as measurement by *in vitro* method to predict the properties of DF is not due to the swelling, hydration, and gelation properties. The effect of fiber on glucose absorption moderation is only determined by the internal structure and surface properties of artichoke fiber, and can be predicted by the simple expression, $R = k'cf/w$, formulated by Eastwood and Morris (1992), which relates the rate of release of nutrients with nutrient concentration within the particles (cf) and particle size (w).

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