PHYSICOCHEMICAL PROPERTIES OF COMMERCIAL FIBRES FROM DIFFERENT SOURCES: A COMPARATIVE APPROACH

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ABSTRACT

The lower intake of fibre and fibre-containing foods has refocused the food industry on the benefits of incorporating different fibres in the foodstuff. Nowadays, a whole range of fibres are available in the market, but sometimes a good choice becomes complicated due to their varied physico-chemical properties. In order to give some light when selecting fibres, a comparative study regarding some physical properties of commercial fibres from different sources is presented, with a view to increasing their use in food products, namely bakery products. Commercial fibres included in this study were hydroxypropylmethylcellulose, cellulose, locust bean gum, guar gum, inulin, galactooligosaccharides, oat and wheat fibres, and fibres extracted from apple and bamboo. Particle size distribution (PSD) of the dry commercial fibres ranged from around 10 to 334 μm; moreover PSD in wet (water and ethanol) form was also determined to have precise information about their behaviour when processing. Cereal fibres (oat 600 and wheat) exhibited the highest values for hydration properties (swelling, water holding and water binding capacity). Only the hydrocolloids (HPMC, locust bean gum and guar gum), with the exception of cellulose, yielded highly viscous solutions during the heating-cooling cycle; moreover oat 600 and apple fibre developed viscous solutions after cooling. HPMC, locust bean gum and guar gum significantly augmented the four SRC values, thus those hydrocolloids affected the relative contributions to water absorption of proteins, carbohydrates, damaged starch and pentosans. Fibre sources and degree of replacement significantly affected the SRC values for the four solvents in all the fibre groups, with the exception of lactic acid SRC in the case of cereal fibres. Differences in fibres effect on wheat flour quality can be easily detected by assessing solvent retention capacity, which can give information on the end use functionality of the wheat flour.

Key words: fibres, physico-chemical properties, hydration, particle size, viscosity.

INTRODUCTION

Substantial research carried out over the last three decades supports the beneficial role of the dietary fibre (DF) in health and nutrition pertaining to reduction in chronic ailments like cardiovascular disease, certain forms of cancer and constipation (Schaafsma, 2004; Lairon et al., 2005). The insoluble fraction of fibres has been related to the intestinal regulation, whereas soluble fibres are associated to the decrease in cholesterol levels and the absorption of intestinal glucose (Rodríguez, Jiménez, Fernández-Bolaños, Guillén, & Heredia, 2006). Hence, DF have gained popularity as food ingredients that provide health benefits (Redgwell & Fischer, 2005; Collar, 2008). Increasing consumer awareness about the potential therapeutical role of the DF has prompted the search of new DF sources. Numerous fibres have been isolated and characterized from completely different sources, and incorporated into different food products (Abdul-Hamid & Siew Luan, 2000; Chau, Wen & Wang, 2006). In fact, nowadays many fibre- enriched products have been launched to the market (Collar, 2008). Fibres have been incorporated in wide variety of foods, like dairy, meat or fish, but bakery products are the preferred source of DF (Abdul-Hamid & Siew Luan, 2000; Sanchez-Alonso, Haji-Maleki & Borderias, 2007).

The physiological functions of the DF are often attributed to their physico-chemical properties, water holding capacity, swelling, rheological and fat binding properties and susceptibility to bacterial degradation or fermentation (Dikeman & Fahey, 2006). In fact, the beneficial healthy effect exerted by soluble fibre, lowering cholesterol and the rate of glucose absorption and post-prandial plasma glucose concentrations, has been associated to their viscosity (Dikeman et al., 2006). Physico-chemical properties of DF also play a fundamental role in their functionality, which has limited their use as food technological agents. The emergence of new fibre sources and also the new processing methods for improving their functionality have widened the applications of fibres in food industry (Chau et al., 2006), and

open new possibilities for designing fibre enriched products and for generating new textures in a range of applications.

Fibres can modify the consistency, texture, rheological properties and sensory characteristics of the fibre supplemented food products (Collar, Rosell, Muguerza & Moulay, 2008). In bakery products, the addition of fibres modifies the breadmaking performance of wheat dough, affecting mixing properties, rheological behaviour and viscometric pattern (Wang, Rosell & Benedito, 2002, Rosell, Santos & Collar, 2006, Collar, Santos & Rosell, 2006, 2007), due to their interaction with the large polymers (starch and proteins) present in the system (Rojas, Rosell & Benedito, 1999; Symons & Brennan, 2004; Rosell & Foegeding, 2007). In general, DF incorporation into water-flour systems could interfere with the protein association and its further aggregation during heating, likely occupying the space of the proteins in the gluten network; and concerning starch behaviour DF affects pasting characteristics of starch such as peak viscosity, breakdown and final viscosity. Those effects are also extended to bakery products where delayed endothermic transition temperatures for both gelatinisation and retrogradation phenomena except for the peak temperature of retrogradation have been described (Santos, Rosell & Collar, 2008). Water holding capacity, particle size distribution and apparent viscosity are repeatedly described as crucial fibre properties with a significant influence in food technology (Nelson, 2001).

The aim of this study was to characterize commercial fibres obtained from different sources concerning their physico-chemical properties (hydration properties, particle size distribution, shape and viscosity) to wide their application in the design of new food formulations, namely, bakery products.

MATERIALS AND METHODS

Commercial fibres included in this study were classified into four different categories of DF, hydrocolloids, oligosaccharides, cereal fibre and fruit-tree fibre sources. Hydrocolloids included hydroxypropylmethylcellulose (HPMC K4M) from Dow Chemical (USA), guar gum from Carob SA (Spain), locust bean gum (Palgum) from Carob SA (Spain) and cellulose powder (Vitacel L) from Barentz Campi y Jové SL (Spain). Oligosaccharides category consisted of inuline (FOS) and polydextrose (GOS, Litesse II) from Danisco Sweeteners (Danisco USA). Cereal fibres comprised fibres from wheat (Vitacel WF600) and oat (Vitacel HF). Falling within the category of fruit and tree fibres, apple (Vitacel AF) provided by Barentz Campi y Jové SL (Spain) and bamboo fibre (Vitacel BAF) from Barentz Campi y Jové SL (Spain) were selected. Dietary fibre composition of those commercial fibres is depicted in Table 1. Commercial blend of Spanish wheat flours of 14.35 % moisture, 0.69 % ash content, 14.76 % protein, 80 Gluten Index, and Chopin Alveograph parameters: Energy of Deformation= 306 x 10^{-4} J, and curve configuration ratio = 0.68 were used. All chemical reagents were of analytical grade.

Fibre chemical characterization and colour

Moisture, protein, ash and fat were determined following the corresponding ICC methods (1994). Carbohydrates were calculated by difference.

The color of the commercial fibres was measured directly in the powder at three different locations by using a Minolta colorimeter (Chroma Meter CR-400/410, Konica Minolta, Japan) after standardization with a white calibration plate (L^* = 96.9, a^* = -0.04, b^* = 1.84). The color was recorded using CIE-L^* a^* b^* uniform color space (CIE-Lab), where L^* indicates lightness, a^* indicates hue on a green (-) to red (+) axis, and b^* indicates hue on a blue (-) to yellow (+) axis. Whiteness was determined using the following formula: whiteness= $100- [(100-L^*)^2 * a^{*2} b^{*2}]^{½}$, according to Park (1995).

Hydration properties

Hydration properties included swelling, water holding capacity and water binding capacity (Nelson, 2001). Swelling or the volume occupied by a known weight of fibre was evaluated

by mixing 5g (± 0.1 mg) of commercial fibre powder with 100mL distilled water and allowing it to hydrate during 16h. Water holding capacity defined as the amount of water retained by the sample without being subjected to any stress was determined suspending 5g (± 0.1 mg) of commercial fibre powder with 100mL distilled water and let them to hydrate overnight; then the hydrated solid was weighed after removing the excess of water and values were expressed as grams of water per gram of solid. Water binding capacity or the amount of water retained by the fibre after it has been subjected to centrifugation was measured as described the AACC method (1994, 56-30).

Particle size distribution

Particle size distribution was determined using a MasterSizer® Laser Diffraction Particle Size Analyzer (Malvern Instrument Ltd, Malvern, England) equipped with MS 15 Sample Presentation Unit (Refractive Index 1.590) for hydrated samples and PS 65 for dry samples. Distributions were made in triplicate for each sample, using 10 to 20 g sample weight for dry particle size distribution and 1 to 2 g in an aqueous suspension for hydrated particle size distribution. Size distribution was quantified as relative volume of particles in size bands presented as size distribution curves (Malvern MasterSizer Micro software v 5.40). PSD parameters recorded included specific surface area, largest particle size (D_{90}), mean particle volume (D_{50}), smallest particle size (D_{10}), Sauter mean diameter (D[3,2]) and mean particle diameter (D[4,3]) as described previously (Afoakwa, Paterson & Fowler, 2008).

Apparent viscosity

Apparent viscosity was determined using the rapid viscoanalyzer (RVA) (Newport Scientific model 4-SA, Warriewood, Australia) by following the ICC Approved Standard 162 (ICC,

1996). Commercial fibre powders (3.5g) were suspended in 25 mL distilled water. Viscosity related parameters were obtained from the recorded plots (Collar, 2003).

Solvent retention capacity

Solvent retention capacity (SRC) defined as the weight of solvent held by wheat flour after centrifugation was determined as described in AACC method (1994, 56-11). The results are expressed as percent of flour weight, on a 14% moisture basis. Four solvents are independently used to produce four SRC values: water SRC, 50% sucrose SRC, 5% sodium carbonate SRC, and 5% lactic acid SRC.

Scanning electron microscopy

The microstructure of the commercial DF was analysed by scanning electron microscopy (SEM). Powder samples were mounted on metal stubs and sputter-coated with 100-200Å thick layer of gold and palladium by Ion Sputter (Bio-Rad SC-500). Sample analysis was performed at an accelerating voltage of 10kV with a SEM Hitachi 4100 from the SCSIE Department of the University of Valencia.

Statistical analysis

All data were presented as mean values of at least three replicates ± standard deviation (SD) and analyzed by nonparametric one-way analysis of variance (ANOVA) using Tukey test ($p<0.05$). When ANOVA indicated significant *F* values, multiple sample comparison was also performed by Tukey HSD test in order to detect significant differences.

RESULTS AND DISCUSSION

Chemical composition of commercial fibres

Eleven commercial DF were used in this study, and their physico-chemical properties compared. They contained different proportions of soluble and insoluble dietary fibres, according to the supplier composition (Table 1). HPMC, locust bean, guar gum, inulin and GOS were considered soluble fibres, whereas cellulose, oat 401, oat 600, wheat and bamboo contained mainly insoluble fibre. Fibre from apple was composed by 25:75 soluble: insoluble fibres.

Regarding the chemical composition (Table 2), the fibres tested contained very low fat content, the highest amount was observed in locust bean and bamboo, which had a fat content of 1.03 and 1.98%, respectively. Ash content varied from 0.01 % observed in GOS to 1.48 % obtained in oat 600. Only higher ash content values were determined in guar gum and oat 401. Wider range was observed in the protein levels that varied from 0.05% (HPMC and GOS) to 6.94% (locust bean). Nevertheless, only locust bean , guar gum and apple fibre showed protein levels higher than 1%.

Chemical composition of the commercial fibres tested revealed their readiness to be used as food ingredients with very low content on ash and fat, and variable content of proteins. In consequence, the carbohydrate content of all the fibres tested was very high, ranged from 82 to 98%, with the exception of locust bean that contained around 79% carbohydrates. Compared to previously reported results, an increase in fibre purity is observed, for instance apple fibre composition was reported 2.45, 1.27 and 7.25% for fat, ash and protein content, respectively (Chen, Rubenthaler, Leung & Baranowski, 1988).

Color of commercial fibres

The color parameters of the fibres are showed in Table 3. Lightness values (L^*) of the fibres ranged from 85.4 to 88.5; with the exception of locust bean gum and apple fibre that showed lower lightness values (80.5 and 54.0, respectively). Lightness of ingredients plays an

important role in bakery products due to consumer preferences. In fact, numerous efforts have been devoted to lighten the color of the grains and grains products (Metzger, 2003).

The hue green (-*a**) varied from 2.2 to 0.22, whereas apple fibre showed the highest redness. The brownish values showed great disparity among the different fibres, having the cellulose the lowest value and the highest value was observed in the apple fibre . The hue yellow (b*) had great variation, but two main groups could be distinguished. Fibres having b* values higher than ten (between 10 and 20) comprised apple, oat 401, GOS and guar gum. In addition, the other fibres had values ranged from three to nine, having the highest value the locust bean gum, whereas cellulose showed the lowest b* value. Whiteness was calculated in order to have better picture of the overall color of the fibres tested. According to whiteness values (Park, 1995), fibres could be grouped into four sets, the higher whiteness values (85-90) were observed in HPMC, cellulose, inulin, oat 600, wheat and bamboo fibres, intermediate (78-80) whiteness values were observed in locust bean and guar gum, and lower whiteness values (67-72) were obtained for GOS and oat 401. Apple fibre was again an exception, showing negative value of whiteness.

Particle size distribution and microstructure

Particle size distribution is of major importance, determining both fibre technological functionality and fibre role in the digestive tract (transit time, fermentation, faecal excretion). The shape, and consequently the size of the fibres, depends on degree of processing and also it may vary during transit in the intestine tract as result of digestion processes. Special attention has been paid to the effect of particle size on breadmaking performance, where fibrous materials have been associated to reduced gas retention and fine bran related to low bread volume, dark crumb color, smooth crust appearance and reduced gritty mouthfeel (Zhang & Moore, 1999). Although for fibres characterization and comparative purposes size

of dry fibres is of interest, they can vary during food processing and some components involved in cohesiveness of the fibre matrix may be solubilised (Guillom & Champ, 2000). Therefore, in the present study, fibres size was determined in dry and wet forms, since some fibres swell in water and their particle size increase, besides alcoholic suspensions were also used for assessing particle size distribution in order to eliminate possible artifacts due to non-fibre components of the commercial powders. The particle size distribution (PSD) of the different commercial powders is presented in Tables 4, 5, 6. Commercial fibres showed great variation in specific surface area, Sauter mean diameter (D[3,2]), mean particle diameter (D[4,3]), the largest mean and the smallest particles size. Very wide variation of PSD was observed in dry and wet dispersion using D_{90} (90% finer than this size). The D_{90} has been used to characterize chocolate powder because its correlation to sensory properties (Afoakwa et al., 2008). The highest particle size (compared using D_{90}) in dry dispersion was observed in GOS, followed by locust bean gum, HPMC and apple fibre. In contrast, bamboo fibre was the smallest one followed by cellulose (Table 4). Oat fibre 401 had smaller PSD than oat 600 and significant higher specific surface area, which was readily evident when comparing their shapes (Figure 1). Oat 401, like locust bean gum, guar gum, apple fibre and HPMC contained particles of very irregular shape, showing structures with rounded edges (Figure 1). Conversely, oat 600, cellulose, wheat and bamboo fibre showed fibrous structures with thread like particles of different sizes. Inulin was comprised of granular particles with numerous aggregates with modular shape, whereas the other oligosaccharide (FOS) contained more angular particles with sharp edges (Figure 1). The volume histograms showed the particle size dispersion of the commercial fibres in dry and wet dispersion (Figure 2). Cellulose showed narrow unimodal distribution accompanied of two very small populations located at lower and higher PS (Figure 2A). HPMC, locust bean gum, guar gum, inulin, oat 600, wheat fibre and bamboo fibre showed narrow unimodal distribution for particle size (only data corresponding

to inulin showed, Figure 2B); whereas wide unimodal distribution was obtained for GOS, oat 401 and apple fibre (showed oat 401).

When particle size was determined in wet form, some variations were observed in the distribution. Using ethanol as dispersant (Table 5), insoluble fibres decreased the smallest particle size (D_{10}), likely due to the solubilization of some contaminant components or the dispersion of some fibre aggregates; in opposition, soluble fibres, regardless guar gum, increased the smallest particle size, presumably due to their partial swelling in ethanol. This effect was particularly significant in the case of oligosaccharides (inulin and GOS), which showed a dramatic increase of the largest PS (D_{90}) in ethanol. In water only the PSD of the insoluble fibres were determined (Table 6), observing a noticeable increase of the largest PS in oat 600, apple and bamboo fibres, surely due to swelling. This result confirmed the absence of soluble material in the commercial fibre powders. There is no general agreement about the more suitable particle size of the fibres for breadmaking products. Some studies concluded that smaller fibre particle size gave better baking performance (Sangnark & Noomhorm, 2003), while other reports described the detrimental effect of fine fibre particles on bread quality (Zhang & Moore, 1999). Only in the case of cellulose a study has been focussed on the effect of particle size of cellulose granules, concluding that granules above the size of 154 μm were recommended for obtaining normal breadmaking properties (Seguchi et al., 2007). However, the PSD of the dry commercial fibres included in this study ranged from around 10 to 334 μm, which might be considered as fine particles according to those previous studies.

Hydration properties

Hydration properties were determined on the commercial powders that contained insoluble fibres. Cereal fibres (oat 600 and wheat) exhibited the highest values for swelling, water holding and water binding capacity (Table 7). Swelling values were comprised within the

279 range 5.5 and 11.9 mL/g reported by Guillon et al. (2000) when listed the hydration
280 characteristics of fibres with different particle size; and the same occurred for the water
281 binding capacity that varied from 3.5 to 6.8 g water/g dry pellet. Oat 401, which has lower
282 particle size distribution and higher specific surface area than oat 600, showed the lowest
283 values for swelling and water holding and water binding capacities. Apple fibre also showed
284 higher swelling and water holding capacity than those of cellulose and bamboo. Concerning
285 the water binding capacity, cellulose showed higher value than the apple fibre and bamboo
286 fibre. Typically, a reduction in the particle size of the dietary fibres has been associated to
287 lower ability to retain water and oil binding capacity (Zhang et al., 1997; Sangnark et al.,
288 2003); although it has been also speculated that in the absence of matrix structure a reduction
289 in the particle size might expose large surface area, and simultaneously more polar groups
290 with water binding sites, to the surrounding water (Chau et al., 2006; Rosell et al., 2006). In
291 the present study, no relationship between hydration properties and PSD was detected; indeed
292 bamboo fibre had the smallest PSD without showing great hydration properties. This result
293 agrees with previous findings that no significant correlation was found between the particle
294 size of inuline (Fibruline), Fibrex (sieve openings 150µm), and pea cell walls fibre (Exafine
295 sieve openings 200-500µm, Swelite sieve openings 100-200µm) and their hydration
296 properties (Rosell et al., 2006). Certainly, no only fibre size determines its hydration, also
297 chemical structure and shape play an essential role (Robertson & Eastwood, 1981). Therefore,
298 general assumption about relationship between PSD and hydration can be only established
299 within fibres subjected to different processes for particle reduction (Chau et al., 2006), and in
300 turn, effect of particle size on water sorption cannot be generalized and must be assessed for
301 each type of fibre (Strange & Onwulata, 2002).
302

303 Hydration properties significantly determine the fate of DF in regulating colonic function and
304 also account for some of their physiological effects (Guillon et al., 2000). In fact, high water
305 binding capacity of DF is related to low digestibility, high volume and weight of feces in *in*
306 *vivo* experiments **(**Wisker, Daniel & Feldheim, 1996; Huang, Sheu, Lee, Chau, 2008).
307 Moreover, high water retention capacity has been associated to reduction in the gelatinization
308 of starch, which is relevant to human nutrition where the degree of starch gelatinization can
309 affect the postprandial sugar availability in foods (Symons et al., 2004). Additionally, liquid
310 retention is of concern to the food industry because it influences ingredients functionality,
311 product yield and shelf stability, being particularly important in the case of baked goods,
312 where water takes part in the phenomena associated to starch gelatinization, protein unfolding
313 and yeast activation during mixing and baking (Rosell et al., 2006; Collar et al., 2007).
314
315 **Apparent viscosity**
316 Fibres contribute to the viscosity of food systems (Dikeman et al., 2006). Viscosity of the
317 commercial fibres were determined using the rapid viscoanalyzer, since it is a very sensitive
318 and descriptive of the processing effects caused by water content and thermal and mechanical
319 input (Whalen, Bason, Booth, Walker & Williams, 1997). Only the hydrocolloids (HPMC,
320 locust bean gum and guar gum), with the exception of cellulose, yielded highly viscous
321 solutions during the heating-cooling cycle (Table 8), although they showed distinct behavior.
322 HPMC increased its viscosity during heating till reached 51°C, where the gelation process
323 takes place (Rosell et al., 2007), and an accentuated decrease of the viscosity is observed that
324 continued till the end of holding period at 95°C; on the subsequent cooling till 50°C a
325 recovery of the viscosity was observed indicating the thermo-reversibility of the gel. Locust
326 bean gum gave high initial viscosity that increased with the temperature, only a decrease in
327 viscosity was observed a short period during cooling from 95°C to 70°C (results not showed),

but further cooling rose again its viscosity. In the case of guar gum, it gave a viscous suspension that did not change during heating and showed a significant viscosity increase during cooling till 50°C. Some viscosity was also developed by apple fibre and oat 600, showing the same pattern than guar gum, that was increasing viscosity only after heating and cooling. It has been reported that apple fibre undergoes irreversible changes during heating, likely due to aggregation of some macromolecules that is responsible of the increased viscosity after cooling, and no gelation is produced after heating and cooling (Chen et al., 1988). In contrast, oat 401 did not increase viscosity, the reduction of the particle size resulted in decreased apparent viscosity (Dikeman et al., 2006). A small decrease of viscosity could be envisaged in the rest of the fibres during heating and cooling, likely due to the thermal and shear constraints. It has been described that inulin also forms gel, but only at concentrations greater than 15% in water at room temperature (Nelson, 2001; Meyer, 2004), which are much higher than the one used in the present study (around 3%). Although cereal fibres, and fruit derived fibres can vary viscosity, plant derived gums are the most widely used as thickening agents to increase the viscosity in food systems (Nelson, 2001). Considering the effect of soluble fibres on the glycaemic response is mostly dependant on their capacity to increase the viscosity of the digest in the gastrointestinal tract (Guillon et al., 2000; Dikeman et al., 2006), hydrocolloids would be the most effective fibres for controlling that response.

Solvent retention capacity

It is clear that fibre functionality in food formulations derived from its interaction and spatial arrangement within the biopolymers system (Redgwell et al., 2005), thus to determine the potential functionality of the commercial fibres in bakery products the four solvent retention profile has been evaluated. This method has been conceived to produce a combined pattern of the four SRC values to establish a practical flour quality/functionality profile that is very

353 useful for predicting baking performance and specification conformance, showing high degree
354 of correlation between SRC methods and other quality parameters (Gaines, 2000). Generally,
355 lactic acid SRC is associated with glutenin characteristics, sodium carbonate SRC is related to
356 levels of damaged starch, and sucrose SRC with pentosan characteristics. Water SRC is
357 influenced by all of those flour constituents. This method has been selected to obtain an
358 overall picture of the effect of different commercial fibres on wheat flour quality concerning
359 its potential in breadmaking performance (Table 9, 10). The replacement of wheat flour by
360 increasing amounts of commercial fibres (5 and 10%) significantly modified the SRC profile
361 of the wheat flour, that effect was significantly dependent on the fibre source and fibre degree
362 (Table 9). The fibre source x fibre degree effects were highly significant for all four solvents
363 in all the fibre groups, with the exception of lactic acid SRC in the case of cereal fibres (Table
364 9). Therefore, differences in fibres effect on wheat flour quality can be easily detected by
365 assessing solvent retention capacity, which can give information about the end use
366 functionality of the wheat flour, since SRC values have been correlated to surgar-snap cookie
367 bake tests and alveograph tests (Guttieri, Bowen, Gannon, O'Brien & Souza, 2001). Fibre
368 SRC behaviour responded to the classification initially suggested (hydrocolloids, prebiotics,
369 cereal fibres, and fruit and tree sources of fibres). With the exception of hydrocolloid group
370 (Table 10), a relatively narrow range of SRC values were obtained for all the solvents, and
371 lactic acid SRC was the least affected value; thus considering the positive correlation between
372 lactic acid SRC and protein quality (Guttieri et al., 2001; Guttieri & Souza, 2003), fibres (with
373 the exception of hydrocolloids) exerted a minor action on protein quality. Fibres acting as
374 prebiotics showed the least effect on SRC, being carbonate SRC and water SRC the most
375 affected values showing a concentration dependent decrease with respect to wheat flour
376 values, and that effect was higher in GOS than inulin. Fibres from cereals, tree and fruits
377 induced a slight increase of sucrose SRC, carbonate SRC and water SRC, and apple fibre

promoted the highest effect. The largest effect on the four SRC values was caused by hydrocolloids, regardless cellulose that showed similar effect to cereal fibres. HPMC, locust bean gum and guar gum significantly increased the four SRC values, being particularly great the effect produced by HPMC on water SRC and the locust bean gum on sucrose SRC, carbonate SRC and lactic acid SRC. Therefore, those hydrocolloids were affecting the relative contributions to water absorption of proteins, carbohydrates, damaged starch and pentosans.

Commercial fibres belonging to different categories (hydrocolloids, oligosaccharides, cereal fibres, and fibres from trees or fruits) showed varied physical enclosed particle size, shape, hydration and viscosity. Particle size distribution of the dry commercial fibres ranged from around 10 to 334 μm; moreover PSD in wet (water and ethanol) form was also determined to have precise information about their behavior when processing. Cereal fibres (oat 600 and wheat) exhibited the highest values for hydration properties (swelling, water holding and water binding capacity) and it was not possible to establish a correlation between PSD and hydration, thus water sorption cannot envisaged from particle size and must be assessed for each type of fibre. The four solvent retention (SRC) profile was assessed for determining the fibres role on flour quality/functionality profile that is very useful for predicting baking performance. The replacement of wheat flour by increasing amounts of commercial fibres (5 and 10%) significantly modified the SRC profile of the wheat flour, that effect was significantly dependent on the fibre source and fibre degree. Differences in fibres effect on wheat flour quality can be easily detected by assessing solvent retention capacity, which can give information about the end use functionality of the wheat flour.

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505 **FIGURE CAPTIONS**

506

507 **Figure 1**. Scanning electron micrographs (x 200 magnification) of different commercial
508 fibres. A: HPMC, B: cellulose, C: locust bean gum, D: guar gum, E: inulin, F: GOS, G: oat
509 401, H: oat 600, I: wheat fibre, J: apple fibre, K: bamboo fibre.

510

511 **Figure 2.** Particle size distribution of several commercial fibres in dry or wet (water, ethanol)
512 suspension. A: cellulose, B: inulin, C: oat 401.

513
514

515 **Table 1**. Dietary fibre composition of the commercial fibres tested. Data from suppliers.
516

Fibers	Total dietary fiber (g/100g)	Soluble (g/100g)	Insoluble (g/100g)
HPMC	100	100	0
Cellulose*	98	1	97
Locust bean	78	78	0
Guar gum	85	85	0
Inulin**	97	97	0
GOS+	90	90	0
Wheat*	97	2.5	94.5
Oat 401*	90	5	85
Oat 600*	96	3	93
Apple*	60	15	45
Bamboo*	97	0	97

* AOAC method

** AOAC method 997.08

+ HPLC

517
518

519

520 **Table 2.** Proximate chemical composition of commercial fibres from different souces.

521

	Chemical composition (g/100g, as is)				
Fibers	**Moisture**	**Fat**	**Ash**	**Proteins**	**Carbohydrates***
HPMC	3.17 ± 0.01	0.04 ± 0.01	0.21 ± 0.01	0.05 ± 0.00	96.53 ± 0.44
Cellulose	5.88 ± 0.01	0.15 ± 0.00	0.14 ± 0.00	0.43 ± 0.02	93.40 ± 0.51
Locust bean gum	12.21 ± 0.01	1.03 ± 0.02	1.02 ± 0.00	6.94 ± 0.07	78.79 ± 0.34
Guar gum	10.91 ± 0.03	0.38 ± 0.02	2.54 ± 0.01	3.82 ± 0.04	82.34 ± 0.01
Inulin	5.73 ± 0.01	0.04 ± 0.01	0.10 ± 0.01	0.21 ± 0.07	93.93 ± 0.10
GOS	1.97 ± 0.01	0.03 ± 0.01	0.01 ± 0.00	0.05 ± 0.00	97.94 ± 0.25
Oat 401	6.61 ± 0.06	0.14 ± 0.03	4.08 ± 0.01	0.75 ± 0.00	88.43 ± 0.75
Oat 600	6.43 ± 0.00	0.04 ± 0.01	1.48 ± 0.00	0.14 ± 0.00	91.92 ± 0.53
Wheat	6.93 ± 0.00	0.10 ± 0.00	0.59 ± 0.00	0.10 ± 0.00	92.28 ± 0.81
Apple	5.87 ± 0.01	0.04 ± 0.01	1.38 ± 0.01	4.82 ± 0.00	87.90 ± 0.54
Bamboo	7.06 ± 0.00	1.98 ± 0.14	0.24 ± 0.00	0.09 ± 0.00	90.63 ± 1.02

522 * calculated by difference

523 * calculated by difference.

524 Mean of three replicates ± standard deviation.

525

526 **Table 3**. Color tristimulus parameters' of different commercial dietary fibres [a]

527

	CIE-Lab			
Fibers	**L***	**a***	**b***	**Whiteness**
HPMC	87.64 ± 0.62 de	-0.66 ± 0.14 ef	3.99 ± 0.07 c	87.99 ± 0.74 fg
Cellulose	88.50 ± 1.88 e	-0.54 ± 0.23 ef	2.85 ± 0.10 a	89.77 ± 1.81 g
Locust bean gum	80.51 ± 0.20 b	-0.46 ± 0.07 f	9.33 ± 0.06 g	79.86 ± 0.20 d
Guar gum	85.38 ± 0.71 c	-1.50 ± 0.01 b	10.24 ± 0.09 h	78.34 ± 0.41 d
Inulin	85.57 ± 0.37 c	-1.23 ± 0.06 c	7.04 ± 0.06 f	83.64 ± 0.48 e
GOS	85.97 ± 1.38 c	-2.16 ± 0.04 a	10.88 ± 0.12 i	71.86 ± 0.74 c
Oat 401	86.24 ± 0.97 cd	-2.21 ± 0.01 a	13.59 ± 0.19 j	67.16 ± 0.23 b
Oat 600	86.02 ± 0.19 c	-1.00 ± 0.06 d	6.43 ± 0.11 e	84.68 ± 0.09 ef
Wheat	85.65 ± 0.95 c	-0.22 ± 0.10 g	4.58 ± 0.06 d	85.78 ± 0.92 efg
Apple	53.95 ± 0.38 a	6.74 ± 0.17 h	20.22 ± 0.35 k	-39.26 ± 5.14 a
Bamboo	87.52 ± 0.15 de	-0.73 ± 0.23 e	3.45 ± 0.02 b	87.29 ± 0.11 fg

[a] Data are the mean values of three replicates ± SD.

528 Means sharing the same letter within a column were not significantly different ($P<0.05$) (n=3).

529

530 **Table 4.** Particle size distribution (PSD) of the commercial fibre powders.

	PSD in dry dispersion					
Fibers	Specific surface area (m^2 g^{-1})	D_{10} (µm)	D_{50} (µm)	D[3,2] (µm)	D[4,3] (µm)	D_{90} (µm)
HPMC	0.1	24.3	89.0	41.6	111.4	232.8
Cellulose	0.2	14.3	40.0	27.8	164.4	97.7
Locust bean gum	0.1	36.8	139.8	70.4	145.0	256.3
Guar gum	0.1	25.7	82.3	43.2	89.1	161.9
Inulin	0.2	17.6	75.9	31.4	85.0	165.6
GOS	0.2	7.2	68.3	35.4	189.9	334.3
Oat 401	0.4	6.7	40.4	14.0	51.0	112.0
Oat 600	0.2	16.2	52.3	28.6	62.6	125.2
Wheat	0.3	13.8	42.2	23.9	61.1	104.9
Apple	0.2	13.1	71.7	28.1	96.3	218.0
Bamboo	0.3	11.5	30.0	17.8	34.3	63.7

D_{10}, D_{50}, D[3,2], D[4,3] and D_{90} represent 10%, 50%, Sauter mean diameter, mean particle diameter and 90% of all particles finer than this size, respectively.

531

532 **Table 5.** Particle size distribution (PSD) of the commercial fibres suspended in ethanol
533 solution.

534

	PSD in ethanol solution					
Fibers	Specific surface area (m^2 g^{-1})	D_{10} (µm)	D_{50} (µm)	D[3,2] (µm)	D[4,3] (µm)	D_{90} (µm)
HPMC	0.1	25.8	101.3	40.5	127.0	267.4
Cellulose	0.3	12.7	38.9	20.7	50.6	100.6
Locust bean gum	0.1	39.9	140.0	62.9	148.2	261.5
Guar gum	0.3	17.0	70.7	23.3	79.1	152.9
Inulin	0.0	86.1	155.9	140.9	170.7	277.6
GOS	0.1	31.0	169.0	49.9	211.6	458.2
Oat 401	0.5	5.9	36.4	12.1	49.1	110.2
Oat 600	0.3	12.8	48.6	19.4	62.2	124.4
Wheat	0.4	11.1	36.6	16.8	45.0	92.9
Apple	0.3	12.6	63.6	22.1	83.7	188.4
Bamboo	0.4	9.1	28.8	14.1	33.6	65.5

D_{10}, D_{50}, D[3,2], D[4,3] and D_{90} represent 10%, 50%, Sauter mean diameter, mean particle diameter and 90% of all particles finer than this size, respectively.

535

536

537 **Table 6.** Particle size distribution (PSD) of the commercial fibres suspended in water.

538

	PSD in water solution					
Fibers	Specific surface area (m^2 g^{-1})	D_{10} (µm)	D_{50} (µm)	D[3,2] (µm)	D[4,3] (µm)	D_{90} (µm)
HPMC	-	-	-	-	-	-
Cellulose	0.3	13.0	39.1	20.5	50.4	105.0
Locust bean gum	-	-	-	-	-	-
Guar gum	-	-	-	-	-	-
Inulin	-	-	-	-	-	-
GOS	-	-	-	-	-	-
Oat 401	0.4	7.4	40.0	14.7	53.3	115.7
Oat 600	0.3	14.8	53.0	23.5	73.1	140.9
Wheat	0.3	12.6	40.2	19.4	50.3	103.7
Apple	0.2	15.3	87.0	34.6	125.0	285.9
Bamboo	0.4	11.3	32.4	16.4	38.7	75.6

D_{10}, D_{50}, D[3,2], D[4,3] and D_{90} represent 10%, 50%, Sauter mean diameter, mean particle diameter and 90% of all particles finer than this size, respectively.

539

540 **Table 7.** Hydration properties of the commercial fibres used in this study

541

Fibers	Swelling (mL/g)		WHC (g water/g solid)		WBC (g water/ g solid)	
HPMC	na		na		na	
Cellulose	6.2 ± 0.60	b	5.57 ± 0.48	c	3.99 ± 0.20	de
Locust bean gum	na		na		na	
Guar gum	na		na		na	
Inulin	11.79 ± 0.79	f	11.05 ± 0.49	f	1.16 ± 0.09	a
GOS	na		na		na	
Oat 401	4.98 ± 0.02	a	3.69 ± 0.16	a	3.11 ± 0.07	b
Oat 600	7.60 ± 0.20	e	6.89 ± 0.04	e	4.79 ± 0.05	f
Wheat	7.07 ± 0.07	cd	6.49 ± 0.12	de	4.15 ± 0.19	e
Apple	6.89 ± 0.11	c	6.12 ± 0.11	d	3.85 ± 0.02	d
Bamboo	5.69 ± 0.11	b	4.83 ± 0.03	b	3.45 ± 0.06	c

Mean of three replicates ± standard deviation

WHC: water holding capacity; WBC: water binding capacity.

na: not available

542 Means sharing the same letter within a column were not significantly different ($P<0.05$) (n=3).

543

544 **Table 8.** Viscometric parameters of different commercial fibres determined by using the rapid
545 viscoanalyzer (RVA).

546

Fibers	Initial Viscosity **(cP)**	Peak viscosity **(cP)**	Visc at 95 **(cP)**	Visc at end 95 **(cP)**	Visc at 50 **(cP)**	Final Visc **(cP)**
Wheat flour	0	2232	248	1572	1847	2433
HPMC	23200	24034	14733	1699	14501	21540
Cellulose	-	-	-	-	-	-
Locust bean gum	19067	23958	22505	23212	22332	24628
Guar gum	3667	4245	3155	3683	9196	11437
Inulin	2	11	-	-	-	-
GOS	-	-	-	-	-	-
Oat 401	3	7	4	-	-	-
Oat 600	4	-	-	-	32	49
Wheat	0	17	-	-	-	-
Apple	2	75	27	66	215	256
Bamboo	3	22	-	-	5	-

547

548

549 **Table 9**. Single and second order interaction significant effects of dietary fibres from different
550 sources added at different degree of flour replacement to blends on the solvent retention
551 capacity.

Source	Solvent retention capacity			
Main effects	Carbonate	Lactic acid	Water	Sucrose
	%	%	%	%
Source (SO)	***	***	***	***
Degree (DG)	***	***	***	***
SO x DG	***	***	***	***
Hydrocolloids (HC)	***	***	***	***
Degree (DG)	***	***	***	***
HC x DG	***	***	***	***
Prebiotics (PB)	***	***	***	***
Degree (DG)	***	**	***	***
PB x DG	***	*	***	***
Cereals (CR)	***	ns	***	*
Degree (DG)	***	*	***	***
CR x DG	**	ns	***	**
Trees & fruits (TF)	***	**	***	***
Degree (DG)	***	**	***	***
TF x DG	***	*	***	***

ns: no significant effect; * significant effect at P<0.05; ** significant effect at P<0.01; *** significant effect at P<0.001.

552

553 **Table 10.** Least squares means with 95% confidence intervals of solvent retention capacity of
554 commercial fibres from different sources added at different degree of flour replacement to
555 blends.

Dietary fiber	Degree	Solvent Retention Capacity (%)			
		Water	Sucrose	Carbonate	Lactic acid
HYDROCOLLOIDS					
Cellulose	0	66.1 a	101.7 a	78.2 a	110.7 bc
	5	68.2 b	106.3 ab	77.9 a	107.7 ab
	10	67.6 b	117.0 c	78.6 ab	98.8 a
HPMC	0	66.1 a	101.7 a	78.2 a	110.7 bc
	5	89.9 e	197.2 g	109.6 d	164.0 e
	10	156.7 h	197.8 h	135.4 g	179.2 gh
Locust bean	0	66.1 a	101.7 a	78.2 a	110.7 bc
	5	84.6 d	153.3 d	129.3 f	173.3 efg
	10	90.6 ef	204.0 i	157.1 h	209.5 i
Guar gum	0	66.1 a	101.7 a	78.2 a	110.7 bc
	5	81.2 c	160.0 e	102.0 c	117.0 bcd
	10	98.4 g	160.7 ef	114.2 e	166.0 ef
PREBIOTICS					
Inulin	0	66.1 d	101.7 cd	78.2 e	110.7 d
	5	66.8 de	100.6 c	73.2 d	106.6 c
	10	63.7 c	101.3 c	67.3 b	112.8 de
GOS	0	66.1 d	101.7 cd	78.2 e	110.7 d
	5	59.5 b	95.0 b	69.1 c	100.6 a
	10	48.9 a	85.4 a	56.6 a	102.4 ab
CEREALS					
Oat 401	0	66.1 a	101.7 a	78.2 a	110.7 defg
	5	72.4 c	112.9 d	81.2 c	104.4 ab
	10	72.4 c	119.1 ef	82.2 cd	106.7 abcd
Oat 600	0	66.1 a	101.7 a	78.2 a	110.7 defg
	5	66.8 ab	104.6 bc	81.1 c	108.3 bcde
	10	76.3 e	121.0 efg	84.1 e	101.9 a
Wheat	0	66.1 a	101.7 a	78.2 a	110.7 defg
	5	66.4 a	104.4 ab	79.3 ab	104.5 abc
	10	73.2 cd	118.5 e	82.0 cd	110.3 cdef
TREES & FRUITS					
Apple	0	66.1 a	101.7 a	78.2 a	110.7 bc
	5	70.2 c	108.9 c	102.2 d	115.2 d
	10	78.5 e	127.5 e	127.8 de	111.2 bc
Bamboo	0	66.1 a	101.7 a	78.2 a	110.7 bc
	5	66.5 ab	106.0 b	79.2 ab	109.7 b
	10	72.5 d	117.5 d	81.8 c	101.0 a

556

557 Means sharing the same letter within a column were not significantly different ($P<0.05$)
558 (n=4).

559