1 **Influence of fibre addition on white sauces made with corn starch. Effect on**
2 **their freezing/thawing stability.**

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14 **Short running title**

15 Stability of fibre-enriched béchamels

16

17 **Abstract**

18 Fibre-enriched white sauces with apple (AF401), potato (KF200) and microcrystalline cellulose
19 (MCC) were selected among six white sauces, all of them elaborated by replacing corn starch and
20 milk with 3% of different dietary fibres. It was investigated the freezing/thawing (F/T) stability of
21 these three enriched white sauces studying their physico-chemical (colour, syneresis percentage,
22 total soluble solids content), rheological (viscoelastic and steady measurements) and sensorial
23 properties before and after a freezing/thawing treatment. White sauce with MCC resulted in being
24 the most like the control (without fibre) showing a higher elasticity and a heat-stability. Moreover,
25 the sauce elaborated with MCC has a sensorial profile as a traditional corn starch sauce with high
26 “creaminess” and lower “heterogeneity” after the F/T treatment. Therefore, the properties provided
27 by MCC make this product interesting in food design, and MCC sauce could be used as an
28 industrial frozen fibre-enriched white sauce.

29 **KEYWORDS**

30 béchamel, rheology, microcrystalline cellulose, freezing stability, sensory properties

31 **Practical Application**

32 These days, there is an increase in the demand of precooked frozen dishes due to current lifestyles,
33 and because the use of fibre exhibits many proven health benefits. A béchamel sauce made from
34 corn starch and enriched with different fibres was elaborated, frozen and thawed in microwave.
35 Both fresh and frozen/thawed microcrystalline cellulose (MCC) sauces exhibited very similar
36 rheological and sensorial properties to an industrial and traditional frozen white sauce without fibre.
37 Therefore, MCC-enriched white sauce resulted to be a feasible strategy to produce a white sauce
38 suitable for frozen dishes with good functional properties and sensorial quality.

39 **Introduction**

40 Nowadays, the lack of time for cooking and the demand for comfort and speed of food
41 production have generated an increase in the requirement of precooked frozen dishes, in which
42 sauces play an important role (Arocas, Sanz, & Fiszman, 2009a; Román, Reguilón, & Gómez,
43 2018). The most common phenomena involved in the destabilisation of sauces entails creaming,
44 flocculation, and coalescence during their preparation and/or storage (Mandala, Savvas, &
45 Kostaropoulos, 2004). These phenomena are of great significance in white or béchamel sauces as
46 they are commercialised in a frozen state and therefore, their long-term frozen storage stability is a
47 crucial purchasing factor for the consumer, who demands high quality products. The white sauce is
48 considered an oil-in-water emulsion with a dispersed phase, formed by oil droplets, and, with a
49 continuous phase formed by the rest of the ingredients, especially the milk proteins and the starch.
50 Both type and content of starch play a fundamental role in the rheological properties and, hence, the
51 final texture of the white sauce (Román et al., 2018; Sanz, Tárrega, & Salvador, 2016) because
52 phenomena of gelatinisation and retrogradation could be responsible for a “runny” or “gummy”
53 texture (Arocas, Sanz, & Fiszman, 2009b).

54 In this sense, previous studies have been carried out, obtaining some advances, in order to
55 diminish the negative effects of these destabilisation phenomena and improve the textural and
56 sensorial properties of white sauces by using different types of native and modified starches (Arocas
57 et al., 2009b; Arocas, Sanz, & Fiszman, 2009c; Arocas, Sanz, Salvador, Varela, & Fiszman, 2010a;
58 Arocas, Sanz, Hernández-Carrión, Hernando, & Fiszman, 2010b), changing processing conditions
59 (Arocas et al., 2009b, 2010b), adding hydrocolloids (Arocas et al., 2009c; Heyman, Depypere,
60 Delbaere, & Dewettinck, 2010) or proteins (Guardeño, Hernando, Llorca, Hernández-Carrión, &
61 Quiles, 2012) and thermally inhibited native starches (Sanz, Tárrega, & Salvador, 2016). Arocas et
62 al. (2009b) found better results with the use of modified starches as they reduced the negative
63 structural changes caused by freezing (decrease in the viscoelastic modulus and higher syneresis).

64 However, today there is a tendency to promote the use of “natural” components like native starches,
65 which present less technological quality, but they have the advantage of not having the status of
66 additives, and of being cheaper.

67 On the other hand, with an increase of scientific evidence, the enrichment of foods with
68 different dietary fibres is also an actual tendency (Augusto, Falguera, Cristianini, & Ibarz, 2011;
69 Elleuch et al., 2011; Zhang & Li, 2018). The addition of the dietary fibres to these type of emulsion-
70 based foods will produce changes in the sauce structure and rheology behaviour, so it is important
71 to study how these changes can affect the stability and sensorial properties of these products. In
72 addition, these effects are dependent fibre type.

73 This work aims to study the effect of dietary fibres on the freezing/thawing stability of a
74 béchamel sauce elaborated from corn starch, to produce a fibre-enriched white sauce while
75 exhibiting similar rheological and sensorial properties to those of an industrial frozen white sauce
76 without fibre intended to be thawed in a microwave.

77

78 **Materials and Methods**

79 **Materials**

80 Native corn starch (Maizena) (Unilever, Barcelona, Spain) and six different fibres [apple
81 (AF150), pea (EF150), oat (HF401), hydroxypropyl methyl cellulose (K4M), potato (KF200), and
82 microcrystalline cellulose gel-811F (MCC)] donated by “Rettenmaier bérica, S.L.” (Barcelona)
83 were initially used in the production of the white sauces. The main technological characteristics of
84 each fibre supplied by the manufacturer are shown in Table S1. The rest of ingredients are
85 powdered skimmed milk (Central Lechera Asturiana, Asturias, Spain), sunflower oil (Koipesol,
86 Madrid, Spain), and salt (sodium chloride).

87

88 **Preparation of white sauce samples**

89 Six fibre-enriched white sauces and one control (without the addition of fibre) were
90 produced following the formula used by Arocas et al. (2009b, 2009c, 2010a, 2010b) with slight
91 modifications, replacing partial amounts of the total of corn starch (4.70%) and milk (9.30%) with
92 3.00% of each fibre (Table 1). Hence, all white sauces samples were a “source of fibre”. According
93 to Regulation (EC) No 1924/2006, a food is a “source of fibre” when “it can only be made where
94 the product contains at least 3 g of fibre per 100 g, or at least 1.5 g of fibre per 100 kcal” (EC 2006).

95 Using a Thermomix TM 31 food processor (Vorwerk España, M.S.L., S.C., Madrid, Spain)
96 all ingredients were heated up to 90°C at 1100 rpm and preserved at 90°C with the same agitation
97 speed for 6 min. Following preparation, each sauce was at once cooled down to 37°C in a Hetofrig
98 CB60VS water-bath (Heto LabEquipment A/S, Birkerød, Denmark). Freshly prepared white sauces
99 were then analysed.

100

101 **Freezing, thawing, and heating procedures**

102 Freezing experiments were based on previous work by Alvarez et al. (2011, 2013); white
103 sauce samples were placed on flat-freezing and microwave-thawing trays and then frozen by forced
104 air convection in a Frigoscandia tunnel (Frigoscandia, S.A., Paris, France) at a freezing rate of 0.91
105 cm/h until their thermal centres reached -24°C. After freezing, the samples were immediately
106 packed in polyethylene plastic bags, sealed under light vacuum (- 0.05 MPa) on a Multivac packing
107 machine (Sepp Haggenmüller KG, Wolfertschwenden, Germany), and placed in a domestic freezer
108 for storage at -24°C, where they stayed for at least one month before thawing.

109 Based on previous research (Alvarez et al., 2017); frozen samples were unpacked and
110 thawed in a Panasonic M1712N (Samsung Electronics S.A., Madrid, Spain) microwave oven. To
111 heat the samples, they were placed in the centred position and irradiated with an output power
112 rating of 700 W. First, each sample was irradiated for 5 min, removed from the microwave and

113 stirred gently (shear rate $\approx 10 \text{ s}^{-1}$) with a spoon to distribute the heat in the sample. Heating of the
114 samples was continued back in the microwave where irradiation was carried out under the same
115 conditions until the thermal centre reached 50°C . After heating, all the frozen/thawed (F/T)
116 products were cooled to 37°C by placing them in the same Hetofrig CB60VS water-bath mentioned
117 above. Samples were tested at 37°C , which was considered an adequate temperature for the
118 consumption of these white sauces.

119 All the white sauces with each fibre type and for each treatment (fresh and F/T samples)
120 were tested in duplicate.

121

122 **Rheological properties**

123 Measurements of steady and oscillatory rheological data were performed using a Kinexus
124 pro rotational rheometer (Malvern Instruments Ltd, Worcestershire, UK), equipped with a cone and
125 plate geometry (4° cone angle, 40 mm diameter). Loaded samples were rested for 5 min before
126 analysis, to ensure both thermal and mechanical equilibrium at the time of measurement. The
127 samples were covered with a very thin film of Vaseline oil (PRS-Codex) to avoid dehydration of
128 them. The temperature was maintained to within 0.1°C by a Peltier element in the lower plate
129 keeping the temperature at 37°C , except when non-isothermal heating processes were carried out.

130

131 **Steady shear rheological measurements**

132 Before measurement, a pre-shear was performed at a shear rate of 100 s^{-1} over 1 min for
133 temperature equilibration, standardisation of the shear rate of each sample, as well as avoiding
134 particle trapping near the tip of the cone (Shelat et al., 2015). Following equilibration, flow curves
135 were obtained for shear rates ranging from 0.1 to 100 s^{-1} at 37°C and 5 points per decade (16 total
136 points). Similar shear rates are commonly reached during chewing and swallowing processes of
137 foods (Shama and Sherman, 1973; Yoshida, Igarashi, Iwasaki, Fuse, & Togashi. 2015). The

138 Ostwald de Waele or the power-law model (Eq. (1)) was used to determine the shear rate effect on
139 the apparent viscosity values of the white sauces:

$$\eta_a = K \dot{\gamma}^{n-1} \quad (1)$$

141 being η_a the apparent viscosity (mPa s), K the consistency coefficient (mPa sⁿ), $\dot{\gamma}$ the shear rate (s⁻¹),
142 and n the flow behaviour index. The apparent viscosity at 50 s⁻¹ (η_{50}) was also obtained from
143 apparent viscosity vs. shear rate curves, which is used to imitate oral conditions (Espinal-Ruiz,
144 Restrepo-Sánchez, Narvaez-Cuenca, & McClements, 2016; Pal, 2011).

145

146 **Small-amplitude oscillatory shear (SAOS) measurements**

147 *Stress sweep tests.* To determine the linear viscoelastic (LVE) region, stress sweeps tests
148 were run at 1 Hz at 37°C with the shear stress (σ) of the input signal varying from 0.1 to 100 Pa
149 (Herranz et al., 2017). Changes in complex modulus (G^*) and loss tangent ($\tan \delta$) were recorded.
150 The critical (maximum) values of shear strain ($\gamma_{\max}$), and shear stress ($\sigma_{\max}$) on the limit of LVE
151 range were derived by the method previously described in Campo-Deaño, Tovar, & Borderias
152 (2010).

153 *Frequency sweep tests.* Samples underwent stress testing that varied harmonically with time
154 at variable frequencies ranging from 10 to 0.1 Hz. The strain amplitude was set at 0.5 % within the
155 LVE range.

156 *Temperature sweep tests.* Temperature sweep tests were performed for dynamic
157 thermomechanical analysis (DTMA) from 20 to 80°C at a linear heating rate (5°C min⁻¹).
158 Frequency (1 Hz) and strain $\gamma = 0.5\%$ (within the LVE range) were fixed.

159 All rheological measurements were carried out at least in quintuplicate.

160

161 **Measurement of syneresis, total soluble solids (TSS) content, and colour**

162 Syneresis percentage was determined by centrifugal force (Alvarez, Fernández, & Canet,
163 2009). 5 g of each white sauce (fresh and frozen/thawed) were put in the centrifuge tubes and
164 subsequently centrifuged (Sorvall RC-728311(GMI, Inc., Ramsey, MN, USA) at 6000 rpm
165 (corresponding to 15000 x g) for 30 min. Syneresis is expressed as the percentage of liquid
166 separated per total weight of the sample in the centrifuge tube (Alvarez et al., 2011, 2013). TSS was
167 determined using a hand-held refractometer Atago dbx-30 (Itabashi-ku, Tokyo, Japan) and the
168 results were expressed in °Brix.

169 Based on previous research (Alvarez et al., 2011, 2017), the colour of the samples was
170 measured with a Hunter-Lab model D25 (Reston, VA) colour difference meter fitted with a 5 cm
171 diameter aperture. Results were expressed following the CIELAB system (D65 illuminant and 10°
172 viewing angle). Lightness (L^*), redness (a^*), and yellowness (b^*) were determined. The total colour
173 difference (ΔE^*) between each F/T sample and its fresh counterpart was calculated following the
174 method of Francis and Clydesdale (Francis & Clydesdale, 1975).

175 All the instrumental measurements were performed at least four times.

176

177 **Sensory analysis**

178 Testing was carried out by a panel of 10 semi-trained panellists. They were chosen among
179 the members of the Characterization, Quality, and Safety department of the ICTAN with a wide
180 experience in descriptive evaluation of semisolid products and they were regular white sauce
181 consumers. The descriptive evaluation used by Arocas et al. (2010a), which is specific for white
182 sauces, was used. Sensory evaluations were carried out in individual booths (ISO 8589:2007).
183 Seven textural attributes (three non-oral and four oral attributes), defined previously by Arocas et al.
184 (2010a) were evaluated. Each panellist received and scored all four freshly prepared and F/T white
185 sauces in separate sessions and by duplicate. Therefore, a total of four separate 60 min sessions

186 were performed. White sauces were presented, one by one in a sequential monadic way, in a
187 randomised order, and each panellist evaluated the group of four sauces heated in a microwave at
188 37°C. The panellists used 8 cm unstructured scales, anchored at the ends with “low” and “high”, to
189 rate the selected seven attributes in the different sauces.

190

191 **Statistical analysis**

192 Application of one-way analysis of variance elicited the effect of replacing corn starch and
193 milk components with each type of fibre at both processing levels (fresh and F/T samples) (Herranz
194 et al., 2017). Also, for each sauce type, all instrumental parameters and sensory attributes were
195 studied for the effect on stability due to freezing/thawing and re-heating of the sample. Minimum
196 significant differences were calculated using Fisher’s least significant difference (LSD) tests with a
197 95% confidence interval for comparison of instrumental parameters and sensory attributes (Alvarez
198 et al., 2011; Herranz et al., 2017). Pearson correlations were established to examine the relationship
199 between the instrumental parameters and sensory attributes.

200 Data analysis was carried out with SPSS Statistics 19.0 (SPSS Inc., Chicago, IL, USA) and
201 XLSTAT add-in for Microsoft Excel software version 2012 (Addinsoft, Paris, France).

202

203 **Results and Discussion**

204 **Selection of fibres**

205 Initially, the flow curves of fresh white sauces, produced with six different fibre types, were
206 obtained to make a fibre-enriched béchamel to replicate, as close as possible, commercial white
207 sauce (made with only corn starch), with optimal textural and sensory properties. All samples
208 showed shear thinning behaviour ($n < 1$), due to the apparent viscosity decreasing as the shear rate
209 increased (Figure 1). This thinning behaviour is typical of starch-based sauces (Arocas et al., 2009b;
210 Mandala et al., 2004; Román et al., 2018; Sanz et al., 2016). The viscosity curves of most samples

211 showed great similarity to the control, sauces produced with K4M and HF401 were an exception to
212 this. Fitting the flow curves to the power law model, the consistency index (K), flow index (n) and
213 the apparent viscosity at 50 s^{-1} (η_{a50}), were obtained (Table 2). This latter parameter has been related
214 to the perception of thickness in the mouth (Morell, Hernando, Llorca, & Fiszman, 2015). As can be
215 seen in Table 2, sauces with K4M and HF401 had the highest and the lowest, significant ($P < 0.05$),
216 K and η_{a50} values, respectively, in comparison with the control sauce without fibre. For this reason,
217 both fibres were not considered for further study. Also, the sauce with pea (EF150) fibre showed a
218 higher consistency than the control, although differences were not significant. However, it was also
219 discarded from the study as it was shown to be an unstable sauce, as their rheological properties
220 changed very quickly as seen by the higher standard deviation of their K and mainly n mean values
221 (17.1 ± 2.54 and 0.243 ± 0.232 , respectively).

222

223 **Rheological characterisation of fibre-enriched white sauces**

224 **Stress sweep tests**

225 Study of the addition of different fibres, and of one cycle of F/T (freezing, storage, and
226 thawing) plus heating, on the LVE range of white sauces, were explored. For that propose shear
227 stress ($\sigma_{\max}$) and shear strain ($\gamma_{\max}$) amplitudes, which can be taken as measurements of rheological
228 stability (Mezger, 2006), complex modulus (G^*) and loss factor ($\tan \delta = G''/G'$) within the LVE
229 range were evaluated (Table 3). Regarding the fresh sauces, the control presented a very stable
230 network with the highest values of both shear stress ($\sigma_{\max}$) and shear strain ($\gamma_{\max}$) amplitudes,
231 followed by MCC-enriched sauce. Thus, the addition of fibres altered the conformational stability
232 to different degrees. Presence of fibres decreased the resistance ($\sigma_{\max}$) and deformability ($\gamma_{\max}$),
233 significantly ($P < 0.05$), of the fresh sauces, but especially those with added AF401 and KF200
234 which were much more unstable. The rigidity (G^*) of fibre-enriched sauces were like that of the
235 control, except for the KF200-enriched sample. Moreover, for all fresh samples the values of $\tan \delta$,

236 which shows the ratio of the amount of energy lost to the amount of energy stored, were lower than
237 one, reflecting a solid-like character. The fibre-enriched sauce whose structural stability appears
238 less affected, with respect to the control, was the MCC-enriched sample. In fact, Zhang (2001)
239 reported that MCC could act as a viscosity-increasing agent, a moisture binder, an emulsion
240 stabiliser, and could help improve the texture of many food products. It seems that when CMC is
241 added to an oil-in-water emulsion at higher concentrations can increase emulsion stability (Cao,
242 Dickinson & Wedlock, 1990). In addition, CMC is physiologically inert and has beneficial effects
243 on lowering glycemic and cholesterol levels (Ou, Kwok, Li, & Fu, 2001; Uskoković, 2008), and
244 therefore its use in formulated products is very attractive (Arancibia, Bayarri & Costell, 2013).

245 In turn, the cycle of freezing/thawing and subsequent heating by the microwave produced a
246 hardening and a structural improvement, as shown by the significant increases ($P < 0.05$) of both
247 shear amplitudes and G^* , and decrease of $\tan \delta$, respectively, with both F/T control and MCC-
248 enriched sauces containing the more stable networks.

249 These results are in accordance with previous data reported by Arocas et al.(2009b) who
250 found that white sauce networks produced with native corn starch were notably affected by a
251 freeze/thaw cycle. In particular, the F/T systems were stiffer (higher $\sigma_{\max}$) and less deformable
252 (lower $\gamma_{\max}$) to the applied stress, which was attributed by the authors just cited to starch
253 retrogradation phenomenon occurring during the freezing process, changing the network structure
254 of the white sauce. Specifically, the use of xanthan and locust bean gums and the subsequent
255 reheating after freezing reduced these structural changes (Arocas et al., 2009c). Therefore, it seems
256 that both the type of fibre and the freezing/thawing affected the conformational stability of the
257 network, formed by corn starch together with proteins and lipids, in different ways. In general, with
258 the addition of the different fibres to the white sauces, they became more rigid but brittle to
259 different degrees. The presence of fibres could hinder the interactions between the starch polymer
260 chains that take place during starch retrogradation (Arocas et al., 2009c).

261 Frequency sweep tests

262 The mechanical spectra of all the samples at 37°C are shown in Figure 2. In general, for
263 fresh samples, storage modulus (G') was less than one order of magnitude greater than the viscous
264 modulus (G''), indicating solid-like character. Moreover, while G' increased slightly with increasing
265 frequency, G'' showed a considerable dependence on frequency, increasing particularly in the high
266 frequency range (3 - 10 Hz), reflecting weak gel behaviour. These spectra were remarkably similar
267 to those obtained for white sauces prepared with different native starches by Sanz et al. (2016), who
268 associated the weaker gel behaviour of the samples made with native corn starch, with the reduced
269 thickening ability of this native starch. Oscillatory spectra of all the studied sauces were also like
270 those obtained for other white model sauces produced with wheat and rice flours (Mandala et al.,
271 2004; Román et al., 2018; Sanz et al., 2016).

272 To quantify the frequency dependence of G' and G'' , they can be fitted to the power law
273 equations (Eq. (1) and (2)):

$$274 \quad G'(f) = G'_0 \cdot f^{n'} \quad (1)$$

$$275 \quad G''(f) = G''_0 \cdot f^{n''} \quad (2)$$

276 where G'_0 and G''_0 are elastic and viscous moduli at a frequency (f) of 1 Hz, and n' and n'' denote the
277 rate of change of G' and G'' respectively with increasing frequency, so both exponents provide
278 conformational network stability (Herranz, Canet, & Alvarez, 2017).

279 Table 4 shows the higher values of n'' exponent regarding n' values in all the fresh samples
280 corroborate the stronger G'' frequency dependence mentioned above, reflecting their weak gel
281 behaviour (Lopes da Silva, & Rao, 2007). On the other hand, between the fresh samples, the sauces
282 prepared with AF401 and KF200 showed higher n' and n'' values than the control sample, while the
283 opposite was true for the MCC-enriched sauce. This result would indicate that MCC-enriched sauce
284 is more stable. Arancibia et al. (2013) found differences in microstructure and particle size
285 distribution between carboxymethyl cellulose (CMC) and tapioca modified starch emulsions and

these differences were clearly related to their rheological behaviour. MCC is a synergistic, co-processed composite consisting of microcrystalline cellulose and carboxymethyl cellulose. CMC-based emulsion exhibited a negative charge of ζ -potential values, especially in emulsions with 5% oil, due to the presence of the anionic groups in the polymer chain of CMC and its surface properties. It is considered that the larger ζ -potential values indicate a higher electrostatic repulsion between the droplets that can increase emulsion stability. Moreover, the addition of CMC to emulsions made with 5% oil produced that the fat droplets were closely associated with one another and clumped together in certain regions giving more structured system.

The freeze/thaw cycle and subsequent heating produced a structural reinforcement of all the sauces networks, where the G' modulus was one order of magnitude greater than G'' (Figure 2) and, at the same time an improvement in conformational network stability as shown by the significant decrease of the n' and n'' values with respect to the corresponding fresh sauces. This structural improvement was also observed by Arocas et al. (2009c) when they added xanthan and locust bean gum in white sauces made with native corn starch. As it was observed in the previous section (stress sweep tests), the F/T MCC-enriched sample resulted as the most stable sauce (lowest value of n'') and more similar to the F/T control, although more rigid.

302

303 **Temperature sweep tests**

To study the network stability of these white sauces during heating (cooking process), temperature sweep tests were carried out. Figure 3 shows the thermal profiles (obtained in the 20 – 80°C) of all the sauces within the LVE range are reported in terms of complex viscosity (η^*), while Figure 4 shows the loss tangent ($\tan \delta$) of the sauces. The thermal profiles of G^* and G' showed the same behaviour as the thermal profiles of η^* with the profiles of G'' being like those of $\tan \delta$ (data not shown).

310 As shown in Figures 3 and 4, and Table 5, three stages can be observed in the thermal
311 profiles of all the fresh white sauces. Before heating ($T_0 = 20^\circ\text{C}$), all samples showed similar $\tan \delta$
312 values although KF200 was the most viscous sample. At early heating temperatures, the complex
313 viscosity values decreased to reach a minimum value at $T_{\text{inflexion1}}$, showing all the sauces similar $\tan$
314 δ values. This decrease in viscosity may be due to an initial modification of the network because of
315 the rupture of weak interactions, such as hydrogen bonds, producing a softening of the structure.
316 This decrease was clearer and longer lasting for fresh sauces with added AF401 and KF200 than for
317 the control sauce (Figure 3). There was a small initial increase in the η^* values, ranging between
318 $T_{\text{inflexion1}}$ and $T_{\text{inflexion2}}$, and with a lesser gradient. Nevertheless, this viscosity increase is especially
319 notable and exponential at higher temperatures ($> T_{\text{inflexion2}}$), producing at the same time a
320 considerable decrease in $\tan \delta$ (Figure 3). Therefore, a continuous structural reinforcement and
321 stability of the network is produced, as shown by the viscoelastic parameters' values. This stronger
322 reinforcement of the network could correspond to a sol-to-gel transition as Debet and Gidley (2006)
323 reported previously, so that a 3-dimensional gel network is constructed from the rest of the amylose
324 molecules, reinforced by strong interactions among the swollen starch particles (Debet and Gidley,
325 2006; Hsu, Lu, & Huang, 2000; Ring, 1985), due to the remains of some ungelatinized starch
326 granules starting to swell, or even amylose molecules dissolving from the swollen starch granules,
327 forming new interactions and increasing the strength of the network (Hsu et al., 2000). In turn,
328 Rayment et al. (1995) stated that the starch particles could act as a rigid filler in the matrix, forming
329 strong interactions with the existing matrix. In any case, it must be considered that in these sauces,
330 there was an earlier network formed during the preparation process, so other ingredients can
331 influence the stability of the network. Moreover, at the end of the heating ($\sim 70\text{-}80^\circ\text{C}$) this increase
332 in G^* could be also partially associated to sample drying because of these high temperatures.

333 This exponential strengthening seems to continue at temperatures higher than 80°C ($> T_F$).
334 This indicates that as temperature increases, stronger interactions are formed in the network and, at

the same time, the sample is partially drying. Processed-samples showed, in general, higher values of viscosity and lower values of $\tan \delta$ (higher viscoelasticity) than their fresh counterparts, along the whole heating process, except for the case of the η^* of the F/T AF401-enriched sauce at $T_{\text{inflexion2}}$, which was lower than that of its fresh counterpart (Table 5).

Regarding the fibre type effect, both fresh KF200 and MCC samples had higher complex viscosity values than the control at both T_0 and $T_{\text{inflexion1}}$ (Figures 3C and 3D). However, at $T_{\text{inflexion2}}$, the AF401-enriched sauce had a significantly higher η^* value (Table 5), while at T_F , the apple-enriched sample resulted being the weakest. Moreover, AF401-enriched sauce also showed the highest value of $\tan \delta$ at T_F (decreased viscoelasticity), meaning that the presence of apple fibre decreased either η^* or the viscoelasticity of the sauce system, being less stable during the heating process and not reaching an adequate texture at elevated temperatures. On the contrary, the MCC-enriched sauces seem to be the most heat-stable, as its behaviour was similar to the control during the whole heating process, reaching similar viscosities and $\tan \delta$ values at similar temperatures (Figure 4). In fact, there were no significant differences between the $T_{\text{inflexion1}}$ and $T_{\text{inflexion2}}$ values corresponding to both the fresh control and MCC-enriched sauces, with both temperatures being significantly lower ($P < 0.05$) than those obtained in the fresh AF401- and KF200-enriched sauces (Table 5). In this regard, MCC fibre was more successful at mimicking the effect of corn starch.

Steady rheometer measurements. Flow behaviour.

The flow curves of fresh and frozen/thawed white sauces enriched with selected fibres are shown in Figure S1. All the F/T white sauces exhibited a shear-thinning flow behaviour ($n < 1$), as was also observed in their fresh counterparts (Figure 1), although viscosity profiles were higher in F/T sauces. As seen in Table 6, the type of fibre had a significant effect on the K and η_{a50} values in both fresh and processed (F/T) samples. In fresh samples, MCC showed similar K and η_{a50} values to the control sample, while KF200-sauces showed a K value similar to that of the MCC-sample but

360 with a significantly higher η_{a50} value than the other fresh sauces, which could also be associated to
361 its higher G^* value derived from the stress sweeps (Table 3). After the freeze/thaw cycle, all sauces
362 exhibited a significant increase of their consistencies (K) and η_{a50} values, although the processing
363 only affected the flow behaviour for the MCC sample, which was significantly lower ($P < 0.05$) in
364 the processed sample than in the fresh. This higher degree of shear thinning behaviour could be
365 related to the formation of a greater number of entanglements in the emulsion (Ma & Boye, 2013)
366 also to a lower particle size (Román et al., 2018). However, Sanz et al. (2016) reported a remarkable
367 decrease in both K and n values after the freeze/thaw cycle in white sauces produced with native
368 starches, therefore, it seems that the heating with a microwave just after the thawing influenced the
369 conformation structural of all samples. It is important to note that after the freeze/thaw cycle, the
370 MCC-enriched sauce showed either significantly higher values of K and η_{a50} or significantly lower
371 n values than those corresponding to the F/T control sample. Arancibia et al. (2013) reported that
372 the addition of CMC to oil in water emulsions significantly increased K values and decreased n
373 values. However, the K and η_{a50} values in the F/T control samples were also significantly higher
374 than in the KF200 and AF401-enriched sauces. These observations corroborate the results of the
375 dynamic measurements (Tables 3 - 5), as both fresh and F/T, MCC-enriched sauces had viscoelastic
376 parameters more like the control samples (reflecting similar stability to shearing), while KF200-
377 enriched sauces produced molecular networks stronger to shear, shown by their higher values of
378 G^* , G'' and η^* .

379

380 **Other quality physical parameters**

381 Table 7 shows the syneresis, the total soluble solids content expressed in °Brix and the
382 colour parameters of white sauces, which are also other important quality parameters to study the
383 influence of the fibre addition in the fresh and processed sauces.

384 Syneresis, the release of water, is a common negative phenomenon observed after the
385 freezing of the starch contained in the sauces and is mainly related to amylose retrogradation
386 (White, Abbas, & Johnson, 1989). In fresh sauces, AF401 shows the highest percentage of
387 syneresis, meaning that the AF401 fibre is less capable of retaining liquid components. The
388 syneresis percentages of the remaining fresh samples were significantly lower ($< 10\%$), and there
389 was no significant difference between the syneresis values of the control and the MCC-enriched
390 sauces, so both MCC and KF200 fibres keep or improve the retention of liquid in the fresh matrices
391 sauces as when compared to corn starch. After freezing/thawing treatment, both F/T control and
392 MCC-enriched sauces had significantly lower syneresis percentages than the processed AF401 and
393 KF200 sauces. However, the freezing/thawing damage significantly ($P < 0.05$) affected the KF200
394 structure as shown by the highest syneresis value for the F/T KF200-enriched sample, while there
395 were no significant differences in syneresis percentages, for the remaining samples of the F/T
396 sauces, and freshly made counterparts. Plus, F/T MCC and control sauces were the samples with the
397 lower syneresis percentages, again reflecting a greater degree of F/T stability. This stability may be
398 due to a higher number of entanglements between the polymer chains of this fibre and the amylose
399 chains, reducing the amylose-amylose interactions. It should be noted that applying microwave
400 heating just after the freeze/thaw cycle, likely decreased the syneresis percentage of all these sauces
401 so that it allowed the breakdown of the interactions between amylose molecules facilitating the re-
402 association between them and fibres through water molecules (Arocas et al., 2009b). At the same
403 time, in both fresh and F/T sauces, there were no significant differences between water soluble
404 compounds of the MCC-enriched sauces and those of the control sauces, which were significantly
405 higher than in the other two enriched sauces.

406 Regarding the colour dataset (Table 7), the colour of the fibres used influences the colour of
407 the sauce. AF401 fibre is a brown powder, and both fresh and F/T AF401-enriched sauces were
408 darker brown in colour, with significantly greater redness and yellowness values and the lowest

409 lightness. On the contrary, both KF200 and MCC fibres were white powders and produced coloured
410 sauces more like the controls. However, both fibre type and processing affected the colour
411 parameters of the sauces in separate ways. In the fresh samples, the lightening caused in the sauce
412 by MCC incorporation was significantly lower than that attributed by KF200 addition, although
413 both sauces had significantly lower L^* values than the control without added fibre. However, after
414 processing the MCC-sauce was a brighter sample without significant differences to the control
415 white sauce. Processing decreased the lightness of control, AF401 and KF200 sauces, but favoured
416 higher L^* values in the sauce with added MCC, which could be partially due to its higher water-
417 holding capacity. However, L^* parameter decreases in F/T control sample respect to fresh sample in
418 spite of it has a high water holding capacity unlike what happens for MCC sample. This
419 phenomenon could be due to that the control sample was more affected by the cycle of
420 freezing/thawing. Nevertheless, in the case of MCC sample, MCC could form bonds with water
421 molecules increasing lightness (L^*).

422 On the other hand, although there are significant differences between both the a^* and b^*
423 values of the different white sauces, as expected, both fresh and F/T samples with added either
424 MCC or KF200 had quite similar negative and positive a^* and b^* values to those of the control
425 sauces. In addition, the processing of the MCC-enriched sauce also reduced the differences in the
426 yellowness of this sample and that of the control one. The total colour differences (ΔE^*), calculated
427 with respect to the fresh counterparts were significantly higher for both F/T sauces made with MCC
428 and KF200 when compared to the control sauce, but in the case of the MCC-enriched sauce the
429 decreased differences between the lightness and the yellowness is due to the freeze/thaw cycle when
430 compared to the control sauce.

431

432 **Sensory textural attributes**

433 Table S2 and Figure 5 show the sensory scores given by the panellists for the non-oral and
434 oral textural properties of both fresh and processed sauces produced with the different fibres. The
435 freeze/thaw cycle produced different sensorial profiles for the white sauces depending on the type
436 of fibre incorporated. With regards to the non-oral sensory attributes of texture in the fresh sauces
437 (Figure 5), and in the case of the consistency the panellists distinguished significantly between
438 MCC and KF200 sauces, with higher scores than the other two samples. Untrained panellists did
439 not distinguish the fresh sauces by their resilience. In the case of graininess, the panellists
440 distinguished significantly between AF401 and MCC sauces, which scored lower and higher,
441 respectively. In the case of oral thickness, the panellists distinguished significantly between AF401,
442 with the lowest score, and the other two fibre-enriched samples. The AF401-enriched sauce also
443 scored lower for mouth coating, although differences between the fresh control, AF401 and KF200
444 samples were not significant for this oral attribute. The MCC-enriched sauce had the highest score
445 for creaminess and presented the lowest heterogeneity, without significant differences between
446 scores for this sample and the control sauce, for both attributes. Therefore, the addition of MCC
447 increased the creaminess of the samples. Creaminess is a pleasant sensation when eating, associated
448 with indicators of richness and high quality, mainly in foods containing fat (Akhtar, Murray,
449 Dickinson, 2006). Therefore, in fresh sauces, the control and MCC sauces (Figures 5a and 5d,
450 respectively) had the most similar sensorial profiles, with only significant differences in their
451 consistencies.

452 In addition, after the freeze/thaw cycle, both the control and MCC sauces maintained the
453 highest scores for creaminess and the lowest for heterogeneity, with both samples also scoring
454 lower for resiliency, graininess, thickness and mouth coating than their fresh counterparts. On the
455 contrary, the F/T KF200 sauce scored the highest for mouth coating, heterogeneity, thickness, and
456 graininess, and the lowest for creaminess and resilience, being the sauce most negatively affected

457 by the freeze/thaw cycle as evidenced by its difference in sensory profile (Figure 5c). The KF200
458 fibre does not seem to interact between amylose molecules, and therefore the freezing increased
459 starch retrogradation in this matrix decreasing its sensory quality.

460 These observations are in accordance with the results obtained from the previous
461 instrumental analyses, reflecting that both fibre type and the freeze/thaw cycle had a significant
462 effect on the sensory textural quality of the white sauces, and that in both fresh and F/T samples the
463 sauce produced with MCC was the most similar to the control sample. In fact, both control and
464 MCC samples, fresh and processed, were more stable sauces with higher creaminess, and in this
465 study, creaminess was positively correlated with $\sigma_{\max}$ ($r = 0.710$) and $\gamma_{\max}$ ($r = 0.733$), while being
466 negatively correlated with syneresis ($r = -0.827$), also, $\gamma_{\max}$ was also negatively correlated with
467 heterogeneity ($r = -0.770$). Characterisation of processed AF401- and KF200-enriched sauces was
468 by their higher graininess, heterogeneity and mouth coating, with mouth coating positively
469 correlated with graininess ($r = 0.928$) and thickness ($r = 0.700$). Finally, resilience was positively
470 correlated with both n' and n'' , $r = 0.793$ and $r = 0.852$, respectively, and negatively with G^* ($r = -$
471 0.862), G'_0 ($r = -0.953$), G''_0 ($r = -0.958$) and η_{a50} ($r = -0.772$). Therefore, there is a good
472 relationship between instrumental measurements and sensorial properties in white sauces depending
473 on the fibre type.

474

475 **Conclusions**

476 The freeze/thaw cycle and subsequent heating produced a structural reinforcement of the
477 networks of all samples (control and enriched with fibres) and, at the same time, an improvement in
478 their conformational stability except in AF401 sample. Both fresh and processed MCC-enriched
479 white sauces showed a greater elasticity and more stable networks than those enriched with AF401
480 and KF200 fibres. Moreover, processed MCC-enriched samples showed higher values of lightness
481 and lower percentage of syneresis like the control one. On the other hand, MCC samples presented

482 a more similar sensory textural profile both before and after the freezing/thawing treatment with
483 higher creaminess and lower heterogeneity than samples enriched with AF401 and KF200.
484 Therefore, the use of MCC in white sauces is a feasible strategy to produce a white sauce enriched
485 with fibre suitable for use in frozen dishes, as evidenced by an adequate freezing/thawing stability
486 and sensorial properties similar to the ones corresponding to the control corn starch based sauce.

487

488 **Author Contributions**

489 Beatriz Herranz and María Dolores Álvarez designed the study and wrote the manuscript. Beatriz
490 Herranz and Adrián Martínez performed rheological analysis. María Dolores Álvarez and Adrián
491 Martínez carried out textural and sensorial analysis. Adrián Martínez performed syneresis, total
492 soluble solids (TSS) content, and colour measurements. All authors interpreted the results, revised
493 and approved the manuscript.

494

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608

609 **Supporting Information**

610 Additional supporting information may be found online in the Supporting Information section at the
611 end of the article.

612

613 **Figure captions**

614 **Figure S1.** Apparent viscosity changes versus shear rate of the fresh and frozen/thawed (F/T) white
615 sauces enriched with different fibres in comparison with the control one.

616

617 **Figure 1.** Apparent viscosity changes versus shear rate of the freshly prepared white sauces
618 enriched with different fibres in comparison with the control one.

619

620 **Figure 2.** Mechanical spectra of the fresh and frozen/thawed (F/T) white sauces: controls without
621 added fibre (a), AF401-enriched sauce (b), KF200-enriched sauce (c) and MCC-enriched sauce (d);
622 Temperature (37 °C)
623 Mean values of six measurements $\pm$ standard deviation.

624

625 **Figure 3.** Complex viscosity as a function of increasing temperature (from 20° to 80° C) of fresh
626 and frozen/thawed white sauces enriched with AF401 (b), KF200 (c) and MCC (d), and control
627 sample (a).

628

629 **Figure 4.** Tan δ as a function of increasing temperature (from 20° to 80° C) of fresh and
630 frozen/thawed white sauces enriched with AF401 (f), KF200 (g) and MCC (h), and control sample
631 (e).

632

633 **Figure 5.** Descriptive sensory parameters of fresh and frozen/thawed sauces enriched with different
634 fibres; (a) control, (b) AF401, (c) KF200 and (d) MCC.

635

636 **Table 1.** Composition of control and enriched-fibre white sauces.

Ingredients (%)	Control sauce	Enriched-fibre sauce
Water	83.22	83.22
Powdered skimmed milk	9.30	7.80
Starch corn ("Maizena")	4.70	3.20
Sunflower oil	2.55	2.55
Salt	0.23	0.23
Fibre	0.00	3.00*

637

638

639 **Table 2.** Effect of the type of fibre on the power law parameters derived from flow curves and the
640 apparent viscosity at shear rate of 50 s^{-1} (η_{a50}) of freshly prepared white sauces.

Fibre type	K (Pa s ⁿ)	n (-)	R^2	η_{a50} (Pa s)
Control	6.34±0.202B	0.325±0.002B	0.992±0.000	0.595±0.017B,C
AF401	2.43±0.081B	0.510±0.050A	0.982±0.003	0.482±0.038C,D
EF150	17.1±2.54B	0.243±0.232B	0.985±0.003	0.825±0.060B
HF401	1.16±0.064C	0.481±0.035A	0.994±0.002	0.189±0.018D
K4M	101±31.7A	0.414±0.076A,B	0.999±0.001	9.96±0.484A
KF200	4.92±1.44B	0.460±0.118A,B	0.996±0.000	0.832±0.090B
MCC	5.55±0.186B	0.398±0.010A,B	0.990±0.001	0.639±0.047B,C

641 A-D Different capital letters in the same column indicate significant differences ($P < 0.05$) among
642 white sauces elaborated with different type of fibre in comparison with the control one.

643

Table 3. Effect of the type of fibre and processing on the limit values of linear viscoelastic (LVE) range of fibre-enriched white sauces.

Fibre type	Processing level	$\sigma_{\max}$ (Pa)	$\gamma'_{\max}$ (%)	G^* (Pa)	$\tan \delta$ (-)
Control	Fresh	2.25±0.022Ab	11.3±1.17Aa	20.1±1.82Bb	0.390±0.039Ba
AF401	Fresh	0.176±0.003Db	0.794±0.136Ca	22.8±3.56Bb	0.482±0.028A,Ba
KF200	Fresh	0.328±0.002Cb	0.485±0.119Ca	70.8±19.5Ab	0.393±0.070Ba
MCC	Fresh	2.15±0.031Bb	7.25±1.93Ba	30.8±6.80Bb	0.548±0.105Aa
Control	F/T	2.59±0.006Ba	3.22±0.227Bb	80.7±5.30Ca	0.222±0.028Bb
AF401	F/T	0.530±0.006Da	1.19±0.265Ca	45.9±10.3Da	0.319±0.045Ab
KF200	F/T	0.807±0.001Ca	0.453±0.053Da	180±19.8Aa	0.292±0.023Aa
MCC	F/T	6.44±0.014Aa	4.85±0.618Aa	134±17.4Ba	0.304±0.027Ab

A-D Effect of fibre type. For the same processing level, different capital letters indicate significant differences ($P < 0.05$) among white sauces elaborated with different type of fibre.

a,b Effect of one freeze/thaw cycle. For the same sauce type, different small letters indicate significant differences ($P < 0.05$) among fresh white sauces and F/T counterparts. F/T: white sauces subjected to a freeze/thaw cycle and microwave heating.

652 **Table 4.** Effect of the type of fibre and processing on the rheological parameters derived from dynamic power law fits of fibre-enriched white sauces.

Fibre type	Processing level	G'_0 (Pa s ^{n'})	n'	R^2	G''_0 (Pa s ^{n''})	n''	R^2
Control	Fresh	27.1±2.04Cb	0.167±0.033Aa	0.977±0.027	8.15±0.564Cb	0.328±0.004Ba	0.994±0.001
AF401	Fresh	17.8±2.88Db	0.212±0.043Aa	0.937±0.040	8.69±0.630Cb	0.389±0.014Aa	0.989±0.006
KF200	Fresh	44.6±0.526Ab	0.206±0.004Aa	0.986±0.001	21.0±0.480Ab	0.343±0.005Ba	0.995±0.000
MCC	Fresh	35.2±4.03Bb	0.156±0.027Aa	0.862±0.035	14.9±1.10Bb	0.267±0.011Ca	0.946±0.008
Control	F/T	95.2±7.42Ca	0.096±0.007A,Bb	0.972±0.004	17.6±1.00Da	0.232±0.006Ab	0.979±0.002
AF401	F/T	159±9.51Ba	0.105±0.032Ab	0.946±0.066	38.6±1.02Ca	0.217±0.022Ab	0.954±0.026
KF200	F/T	253±36.6Aa	0.113±0.003Ab	0.960±0.026	68.3±2.63Aa	0.212±0.007Ab	0.969±0.003
MCC	F/T	261±19.4Aa	0.069±2.75Bb	0.965±0.008	45.6±3.02Ba	0.160±0.006Bb	0.933±0.006

653 A-D Effect of fibre type. For the same processing level, different capital letters indicate significant differences ($P < 0.05$) among white sauces
654 elaborated with different type of fibre.

655 a,b Effect of one freeze/thaw cycle. For the same sauce type, different small letters indicate significant differences ($P < 0.05$) among fresh white sauces
656 and their F/T counterparts. F/T: white sauces subjected to a freezing/thawing cycle and microwave heating.

Table 5. Effect of the type of fibre and processing on the rheological properties in the LVE range from thermo-mechanical analyses of fibre-enriched white sauces.

Fibre type	Processing level	$\eta^*_{T_0}$ (Pa s)	$\tan \delta_{T_0}$ (-)	$T_{\text{inflexion1}}$	$\eta^*_{T_{\text{inflexion1}}}$ (Pa s)	$\tan \delta_{T_{\text{inflexion1}}}$ (-)	$T_{\text{inflexion2}}$	$\eta^*_{T_{\text{inflexion2}}}$ (Pa s)	$\tan \delta_{T_{\text{inflexion2}}}$ (-)	$\eta^*_{T_F}$ (Pa s)	$\tan \delta_{T_F}$ (-)
Control	Fresh	4.36±0.596Bb	0.400±0.010Aa	48.2±1.34Ca	3.00±0.339B,Cb	0.380±0.010Aa	63.3±3.15Ba	10.4±0.050Cb	0.360±0.0001Ba	1830±520Aa	0.257±0.030Ba
AF401	Fresh	4.47±1.39Bb	0.513±0.107Aa	53.9±0.949A,Ba	2.46±0.907Cb	0.527±0.102Aa	70.5±2.08Aa	40.9±0.040Aa	0.403±0.010Aa	448±173Ba	0.363±0.020Aa
KF200	Fresh	9.05±1.35Ab	0.363±0.040Aa	56.9±3.03Aa	5.07±0.610Ab	0.417±0.040Aa	69.1±1.91Aa	15.9±1.01Bb	0.380±0.020A,Ba	1001±387A,Ba	0.293±0.030Ba
MCC	Fresh	6.65±0.424A,Bb	0.420±0.03Aa	48.7±2.02B,Ca	4.32±0.546A,Bb	0.447±0.040Aa	64.3±1.65Ba	14.6±1.19Bb	0.403±0.010Aa	1519±125Ab	0.280±0.010Ba
Control	F/T	18.7±0.962Ba	0.153±0.010Bb	47.9±3.55Ba	15.7±1.27Ba	0.163±0.02Bb	60.2±1.69Aa	25.8±2.62Ba	0.223±0.010Bb	2313±88.5Aa	0.230±0.020Ba
AF401	F/T	17.2±6.30Ba	0.223±0.010Ab	58.5±3.81Aa	8.35±3.13Ba	0.313±0.03Ab	66.4±3.98Aa	25.0±7.76Bb	0.410±0.020Aa	949±405Ba	0.320±0.030Aa
KF200	F/T	47.5±12.0Aa	0.230±0.020Ab	55.9±2.25A,Ba	26.5±5.54Aa	0.347±0.04Aa	66.8±2.29Aa	54.8±13.3Aa	0.367±0.020Aa	1338±569Ba	0.267±0.020A,Ba
MCC	F/T	33.1±1.48A,Ba	0.167±0.020Ab	50.1±3.05A,Ba	25.5±3.12Aa	0.207±0.01Ab	59.1±3.78Aa	37.5±2.12Aa	0.267±0.020Bb	3152±569Ba	0.267±0.020A,Ba

A-C Effect of fibre type. For the same processing level, different capital letters indicate significant differences ($P < 0.05$) among white sauces elaborated with different type of fibre.

a,b Effect of one freeze/thaw cycle. For the same sauce type, different small letters indicate significant differences ($P < 0.05$) among white sauces with different processing level (fresh and F/T samples). F/T: white sauces subjected to a freezing/thawing cycle and microwave heating.

T_0 : initial temperature (20 °C); T_F : final temperature (80 °C). $T_{\text{inflexion1}}$ and $T_{\text{inflexion2}}$: points of inflexion along the heating process (20-80 °C).

Table 6. Effect of type of fibre and processing on the power law parameters derived from the flow curves and the apparent viscosity at shear rate of 50 s^{-1} (η_{a50}) of fibre-enriched white sauces.

Fibre type	Processing level	K (Pa s^n)	n (-)	R^2	$\eta_{a,50}$ (Pa s)
Control	Fresh	6.34±0.202Ab	0.325±0.002Ba	0.992±0.000	0.595±0.017Bb
AF401	Fresh	2.43±0.081Cb	0.510±0.050Aa	0.982±0.003	0.482±0.038Cb
KF200	Fresh	4.92±1.44Bb	0.460±0.118Aa	0.996±0.000	0.832±0.090Ab
MCC	Fresh	5.55±0.186A,Bb	0.398±0.010A,Ba	0.990±0.001	0.639±0.047Bb
Control	F/T	15.8±0.223Ba	0.352±0.024Ca	0.991±0.009	1.45±0.078Ba
AF401	F/T	6.77±0.255Da	0.500±0.004Aa	0.989±0.002	1.17±0.045Ca
KF200	F/T	9.65±0.700Ca	0.472±0.004Ba	0.998±0.000	1.38±0.077Ba
MCC	F/T	32.2±0.150Aa	0.286±0.005Db	0.998±0.000	2.03±0.052Aa

A-D Effect of fibre type. For the same processing level, different capital letters indicate significant differences ($P < 0.05$) among white sauces elaborated with different type of fibre.

a,b Effect of one freeze/thaw cycle. For the same sauce type, different small letters indicate significant differences ($P < 0.05$) among fresh white sauces and their F/T counterparts. F/T: white sauces subjected to a freezing/thawing cycle and microwave heating.

Table 7. Effect of type of fibre and processing on the syneresis, soluble solids content and colour of fibre-enriched white sauces.

Fibre type	Processing level	Syneresis (%)	°Brix	<i>L</i> *	<i>a</i> *	<i>b</i> *	ΔE^*
Control	Fresh	6.88±0.259Ba	17.4±1.02Aa	80.3±0.039Aa	-3.36±0.030Ca	4.39±0.159Ca	-
AF401	Fresh	24.9±0.908Aa	12.3±1.29Ca	59.9±0.211Da	4.34±0.176Ab	13.0±0.452Ab	-
KF200	Fresh	5.72±0.171Cb	15.2±0.651Ba	78.2±0.063Ba	-3.32±0.093Cb	3.98±0.153Db	-
MCC	Fresh	6.68±0.259Ba	17.4±0.208Ab	70.3±0.182Cb	-1.03±0.066Ba	8.03±0.096Ba	-
Control	F/T	5.01±0.348Db	18.0±0.971Aa	78.9±0.840Ab	-3.95±0.108Db	2.35±0.666Db	2.62±0.920C
AF401	F/T	22.5±0.561Bb	10.8±0.321Ca	58.9±0.169Cb	5.25±0.007Aa	14.9±0.172Aa	2.36±0.210C
KF200	F/T	23.5±0.687Aa	13.4±0.451Bb	72.8±0.407Bb	-0.92±0.100Ba	8.42±0.310Ba	9.15±0.110B
MCC	F/T	6.67±0.013Ca	18.8±0.624Aa	79.3±0.241Aa	-2.99±0.017Cb	3.28±0.305Cb	10.3±0.070A

A-D Effect of fibre type. For the same processing level, different capital letters indicate significant differences ($P < 0.05$) among white sauces elaborated with different type of fibre.

a,b Effect of one freeze/thaw cycle. For the same sauce type, different small letters indicate significant differences ($P < 0.05$) among fresh white sauces and their F/T counterparts. F/T: white sauces subjected to a freezing/thawing cycle and microwave heating.

*L**: lightness (whiteness); *a**: grade of green/red; *b**: grade of blue/yellow; ΔE^* : total colour difference between each frozen/thawed white sauce and its fresh counterpart.

Table S1. Technological properties of the different fibres used in the elaboration of white sauces.

Fibre	Source	Size/ length (μm)	Purity (%)	Solubility (%)	Apparent density (g/L)	Water retention capacity (%)
AF401	apple	90% particles < 30	60	75% I; 25% S	300	500
EF150	pea	30 - 300		min. 65% I; 0.5% S	350 - 550	600 - 900
HF401	oat	250 - 400	96	—	300 - 440	350
K4M	hydroxypropyl methyl cellulose	—	—	100% S	—	—
KF200	potato	80 - 250	62	56% I 6% S	200 - 400	1200
MCC	microcrystalline cellulose-811F	—	—	—	—	—

I: insoluble; S: soluble.

Table S2. Effect of the addition of fibre and processing on the textural attributes (non-oral and oral) of fibre-enriched white sauces.

Fibre type	Processing level	No oral textural properties			Oral textural properties			
		Consistency	Resilience	Graininess	Thickness	Heterogeneity	Creaminess	Mouth coating
Control	Fresh	2.78±1.07Ba	5.60±0.572Aa	4.80±1.33A,Ba	3.68±1.23A,Ba	1.33±0.806B,Ca	5.60±1.31Aa	3.33±1.67A,Ba
AF401	Fresh	2.38±0.918Ba	5.93±1.12Aa	3.23±1.15Ba	2.18±1.16Ba	3.13±1.81A,Ba	2.58±0.655Ba	2.10±1.11Bb
KF200	Fresh	5.43±0.842Ab	5.58±0.780Aa	4.78±0.988A,Ba	4.58±1.73Aa	4.28±1.18Aa	3.50±1.13Ba	3.93±2.41A,Ba
MCC	Fresh	5.93±0.655Aa	4.88±0.640Aa	5.48±1.24Aa	5.40±1.07Aa	1.18±0.929Ca	6.95±0.532Aa	5.05±1.48Aa
Control	F/T	4.08±0.946Ba	4.00±0.356Ab	3.45±0.714Ba	2.28±0.772Ba	1.88±0.603Ca	5.78±0.556Aa	2.75±0.603B,Ca
AF401	F/T	2.58±0.690Ca	2.93±0.763Bb	4.48±2.24A,Ba	2.40±0.245Ba	3.43±0.222Ba	3.03±0.900Ba	3.75±0.412Ba
KF200	F/T	6.90±0.392Aa	0.750±0.332Cb	5.65±0.911Aa	4.25±0.580Aa	5.70±0.702Aa	1.20±0.469Cb	5.65±0.933Aa
MCC	F/T	6.10±0.535Aa	2.38±0.435Bb	2.43±0.929Bb	2.45±0.794Bb	1.23±0.403Ca	6.48±0.624Aa	2.05±0.785Cb

A-C Effect of fibre type. For the same processing level, different capital letters indicate significant differences ($P < 0.05$) among white sauces elaborated with different type of fibre.

a,b Effect of one freeze/thaw cycle. For the same sauce type, different small letters indicate significant differences ($P < 0.05$) among fresh white sauces and their F/T counterparts. F/T: white sauces subjected to a freezing/thawing cycle and microwave heating.

Figure 1. Apparent viscosity changes versus shear rate of the freshly prepared white sauces enriched with different fibres in comparison with the control one.

Figure 2. Mechanical spectra of the fresh and frozen/thawed (F/T) white sauces: controls without added fibre (a), AF401-enriched sauce (b), KF200-enriched sauce (c) and MCC-enriched sauce (d); Temperature (37 °C). Mean values of six measurements $\pm$ standard deviation.

Figure 3. Complex viscosity as a function of increasing temperature (from 20° to 80° C) of fresh and frozen/thawed white sauces enriched with AF401 (b), KF200 (c) and MCC (d), and control sample (a).

Figure 4. $\tan \delta$ as a function of increasing temperature (from 20° to 80° C) of fresh and frozen/thawed white sauces enriched with AF401 (f), KF200 (g) and MCC (h), and control sample (e).

Figure 5. Descriptive sensory parameters of fresh and frozen/thawed sauces enriched with different fibres; (a) control, (b) AF401, (c) KF200 and (d) MCC.

Figure S1. Apparent viscosity changes versus shear rate of the fresh and frozen/thawed (F/T) white sauces enriched with different fibres in comparison with the control one.