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# Impacts of the size distributions and protein contents of the native wheat powders in their structuration behaviour by wet agglomeration

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## 28 1. Introduction

29

30 The wet agglomeration process is broadly used in a wide range of industrial applications (e.g.  
31 food processing, pharmaceutical industry, chemical and civil engineering, etc.). This process  
32 is used to increase the diameter of particles by adding a wetting liquid and mechanical energy  
33 to promote attractive interactions and mobility (Iveson et al., 2001). The wet agglomeration  
34 mechanisms present a multifactorial inference of many interacting variables, responsible of  
35 the process complexity (Benali et al., 2009; Palzer, 2011). The knowledge and the modelling  
36 of mechanisms involved in the agglomeration processes widely progressed since about  
37 twenty years (Sanders et al., 2009; Washino et al., 2013). The twin product/process  
38 approaches, developed within the framework of science and technology of powders, allow  
39 purposing dimensional and process control tools, which help to solve the industrial  
40 challenges (Hapgood et al., 2009; Mangwandi et al., 2012). These approaches improve very  
41 effectively empiricism even guided by the experimental designs.

42 The development of population balance approaches have allowed ensuring a complete  
43 prediction of the size distribution of the agglomerates (Gerstlauer et al., 2006; Tan et al.,  
44 2005). This approach remain based on a simplified phenomenology and very dependent on  
45 the capacity to estimate the values of the kernel coefficients (Braumann et al., 2010). The  
46 increase of the size is relatively well mastered at lab scale and it is possible to predict values  
47 such as the median diameter of the agglomerates.

48 The investigation of the agglomeration mechanisms also requires taking into consideration  
49 the changes in the morphology or the hydro-textural characteristics of the agglomerates, such  
50 as the compactness or the sphericity. Among the multiple phenomena occurring  
51 simultaneously during the wet agglomeration, how to identify *a priori* the limiting  
52 phenomenon or the preferential reactive mechanisms?

53 The wet agglomeration process requires the addition of water to generate capillary bridges,  
54 which promotes the cohesion between particles. Agglomeration mechanisms result from the  
55 spatial arrangement of the native particles with the binder components, promoting attractive  
56 interactions and links. The contribution of liquid bridges between native particles largely  
57 overtakes the physical forces and the van der Waals interactions (Hapgood et al., 2003). For  
58 food powders, besides the contribution of physical phenomena, the mechanisms also depend  
59 on the physicochemical reactivity of the molecules, which strengthens the adhesion forces  
60 between particles, by adding a significant contribution of the viscous forces (Cuq et al.,  
61 2013). When the food powders are hydrated, some of their molecules are able to undergo

62 irreversible physicochemical changes, such as solubilisation. The molecules have the  
63 capacity to establish with the surrounding molecules low energy interactions including  
64 hydrogen bonds, hydrophobic interactions, or ionic interactions. For examples, the wheat  
65 proteins can establish continuous macromolecular network when subjected to water addition  
66 and mixing, that contribute to irreversible mechanisms (Abecassis et al., 2012).

67 The couscous grains, a typical Mediterranean foodstuff, are produced by agglomeration  
68 process from durum wheat semolina. Recent works demonstrated different modes of  
69 agglomerate morphogenesis during the wet agglomeration of durum wheat semolina to  
70 produce couscous grains (Barkouti et al., 2014; Hafsa et al., 2015; Saad et al., 2011).  
71 Agglomeration mechanisms developed during the wetting/mixing of durum wheat semolina  
72 generated differences in agglomerated structures. Their multiplicity leads to a very large  
73 polydispersity of the size of the wet agglomerates. This is at the origin of the very high ratio  
74 (up to 60%) of out of scope of wet agglomerates (too large or too small) that are observed  
75 during the industrial processing of the couscous grains. A narrow size distribution of the  
76 agglomerates is one of the main quality criteria for the elaboration. The quantification of the  
77 fluctuations in these parameters around their mean values stays a challenge.

78 Only few works deal to describe the influence of the characteristics (size distribution and  
79 protein content) of native semolina on the wet agglomeration process, in order to investigate  
80 the specific contributions of the physical and biochemical mechanisms. Lefkir et al. (2017)  
81 have compared the ability of three different durum wheat semolina of industrial quality to be  
82 agglomerated. The yield of the wet agglomeration was significantly affected by the  
83 characteristics of native semolina, although it was not possible to know if it was an effect of  
84 the protein content or of size distribution of the semolina.

85 The aim of this work is to describe the wet agglomeration mechanisms by analysing the  
86 experimental investigations, to understand how the initial characteristics (particle-size  
87 distribution and protein content) of the native durum wheat semolina impact the  
88 characteristics of the wet agglomerates. Experiments were conducted using different durum  
89 wheat semolina, with different size characteristics or protein contents. The wet agglomeration  
90 process was conducted by using a low shear mechanical mixer. Wet agglomerates are  
91 considered as multiphase media described as a solid granular matrix that could be saturated  
92 or unsaturated by two fluids: liquid and gaseous phases (Rondet, 2008; Ruiz et al., 2011). The  
93 hydro-textural states of the wet agglomerates are defined by the distribution of the values of  
94 water content ( $w$ ), compactness ( $\phi$ ) and saturation degree ( $S$ ).

95

## 96 **2. Material and methods**

97

### 98 *2.1. Raw material*

99 Durum wheat semolina of industrial quality (Panzani group, France) was used as "standard  
100 semolina". Four fractions of semolina with different particle size distributions were obtained  
101 by sieving the standard semolina over a column of 2 metallic sieves (0.315 and 0.25 mm).  
102 The fraction called "small semolina" was collected under the 0.25 mm sieve. The fraction  
103 called "low span semolina" was collected between the two sieves (0.25 and 0.315 mm). The  
104 fraction called "very coarse semolina" was collected over the 0.315 mm sieve. In addition,  
105 the fraction called "coarse semolina" was collected over the 0.25 mm sieve, after sieving the  
106 standard semolina over only one sieve at 0.25 mm. Three durum wheat semolina with  
107 different protein contents (called "very low protein semolina", "low protein semolina", and  
108 "high protein semolina") were also selected. These semolina were produced according to a  
109 standard milling process, using the durum mill pilot plant facility of the technological  
110 platform of the UMR IATE (Montpellier), from three different specific durum wheat grains  
111 (Miradoux, Dakter and Anvergur, respectively) produced in 2015 by the UMR AGIR  
112 (Toulouse) under the ANR Dur-Dur research project. All the semolina were stored in  
113 hermetic containers at 4°C until experiments.

114 The selected semolina were characterized using standardized methods (Table 1). The water  
115 content was determined according to the approved method 44-15A (AACC, 2000), by  
116 weighing after oven drying at 105°C for 24 h. The particle size distributions and their  
117 characteristics values ( $d_{10}$ ,  $d_{50}$  and  $d_{90}$ ) were measured by a laser particle size analyser  
118 (Coulter TMLS 230, Malvern, England) at room temperature. The true density ( $\rho_s^*$ ) was  
119 measured by using a nitrogen pycnometer. The total nitrogen content (TN) of semolina was  
120 determined by the Kjeldahl method, and the crude protein content was calculated according  
121 to  $TN \times 5.7$  based on the AFNOR method V 03-050 (AFNOR, 1970). All experimental  
122 measurements were carried out in triplicate.

123 The selected raw materials allow studying separately the effects of selected variables (median  
124 diameter, span, or protein content) to understand the effects of the physical and biochemical  
125 characteristics of the native particles on the wet agglomeration mechanisms.

126

127

### 128 *2.2. Wet agglomeration process*

129 The wet agglomeration of durum wheat semolina was carried out in a horizontal low shear  
130 mixer (Sercom, France) composed by a mixing a horizontal shaft axis positioned at 6.7 cm  
131 from the bottom of the tank (30 cm length, 11.5 cm width, 16.5 cm height), with 14 metal  
132 rotating paddle blades (4 cm length, 2 cm width, 7.5 cm gap between 2 blades) (Fig. 1). The  
133 direction of rotation of the shaft axis was inverted every 20 seconds to improve the effects of  
134 mixing and homogenization of the powder. The process can be qualified as low shear mixer  
135 because the mixing conditions do not lead to shear stresses as intense as those sitting within  
136 high shear mixers (Rondet et al., 2012).

137 A sample of 780 g of semolina was introduced in the mixing tank and first mixed for 2 min at  
138 constant mixer arm speed (100 rpm) to equilibrate the temperature at 20°C. The wet  
139 agglomeration was conducted at 100 rpm. Water was directly sprayed over the semolina  
140 under mixing, using a single-fluid atomizing system (Spraying Systems Co., France, ref. TPU  
141 6501) to produce a flat spray of droplets. The flat spray nozzle was either connected to a  
142 regular water supply network with a stable pressure or to a peristaltic pump (520S/REM,  
143 Watson Marlow, France) in order to control the liquid flow rate. The water addition flow rate  
144 was  $2.10^{-6} \text{ m}^3 \cdot \text{s}^{-1}$  and the diameter of droplets of water was estimated at 242  $\mu\text{m}$  according to  
145 Mandato et al. (2012). The calculated  $d_{50\text{semolina}}/d_{50\text{droplet}}$  ratio was found to range between 0.5  
146 when using the small semolina, and 1.6 when using the very coarse semolina. These process  
147 conditions induced a value of the dimensionless spray flux ( $\psi_a$ ) close to 0.1 (Litster et al.,  
148 2001). Taking into consideration the characteristics of the liquid and the native powders, the  
149 ratio of drop penetration time to granular circulation time was estimated close to 0.01,  
150 whatever the semolina tested. When depicting these values on the nucleation regime map  
151 (Hapgood et al., 2003), the nucleation regime could be located just near the drop controlled  
152 zone.

153 The spraying time (about 2 min) was adjusted with respect to the targeted water content of  
154 the wet mass (0.45 g water/g dry matter). After the water addition step, a mixing stage at 100  
155 rpm for 10 minutes was conducted to homogenize the entire wet mass. Samples of the wet  
156 agglomerates were collected immediately after the end of the mixing step.

157

158

### 159 2.3. Agglomerates characterization

160 *Size distribution* - Size distribution of the wet agglomerates was measured immediately after  
161 completing the wet agglomeration process. Samples of 250 g were collected and sieved over

162 a column of eleven metallic sieves of decreasing mesh  $D_j \in (2, 1.25, 0.9, 0.8, 0.71, 0.63, 0.5,$   
163  $0.4, 0.315, 0.25,$  and  $0.160$  mm) to separate the different structures. The subscript  $j$  refers to  
164 the sieve number according to the mesh openings. The sieve column was manually shaken  
165 for 2 min. The size distribution was obtained by weighing the mass of the products collected  
166 on each sieve. The weight distribution according to size criteria was expressed as the percent  
167 of total weight. Measurements were conducted in triplicate. Immediately after sieving,  
168 products were sampled from the remaining on the sieves with 2, 1.25, 0.9, 0.8, 0.71 mm mesh  
169 openings, and are then characterized by their water content ( $w_j$ ) and compactness ( $\phi_j$ ).

170

171 *Water content* - The water content (g water / g dry matter) of wet agglomerates was  
172 determined on 3-5 g samples, by a drying method in an oven (RB 360, WC Heraeus GmbH,  
173 Hanau, Germany) at 105°C for 24 h (AACC Method 44-15A). Mean values were determined  
174 from triplicate.

175

176 *Compactness* - The compactness (*i.e.* the solid volume fraction:  $\phi = \rho_s / \rho_s^*$ ) of wet  
177 agglomerates was determined on about 1 g samples, according to [Rondet et al. \(2009\)](#). The  
178 solid apparent density of the wet agglomerates ( $\rho_s$ ) was measured by using a hydrostatic  
179 balance with paraffin oil, which ensures the wet agglomerates without penetrating them.

180

181 *Saturation degree* - The saturation degree is the ratio of the liquid volume to the pore volume  
182 of agglomerates:  $S = V_w / (V - V_s)$ , where  $V_s$  and  $V_w$  are respectively the volume of the solid  
183 phase and the volume of the liquid phase, in the apparent volume  $V$  of the agglomerate.

184

#### 185 *2.4. Statistical analysis*

186 The statistical significance of results was assessed using single factor analysis of variance  
187 (ANOVA). Multiple comparisons were performed by calculating the least significant  
188 difference using Microsoft Excel 2010, at a 5% significance level.

189

190

191

### 192 3. Results

193

#### 194 3.1. Agglomeration of standard semolina

195 In the investigated experimental conditions (mean water content  $\bar{w} = 0.44$ ), the wet-  
196 agglomeration process of the standard semolina gives the size distribution of wet  
197 agglomerates depicted in [Figure 2](#). The wet agglomerates are characterized by a large  
198 dispersion in size, from 200 to 2500  $\mu\text{m}$ . The shape of the curve of the particle size  
199 distribution is clearly not unimodal, with the formation of different structures at  
200 characteristics diameters.

201 The water content and compactness of the wet structure (with diameter up to 710  $\mu\text{m}$ ) were  
202 measured for each class as a function to their diameter ([Fig. 3](#)). The water content of the wet  
203 structures was positively linearly correlated with their diameter ([Fig. 3a](#)). The compactness of  
204 the wet agglomerates was negatively linearly correlated with their diameter ([Fig. 3b](#)).  
205 Previous works have already demonstrated that in almost comparable process conditions, the  
206 agglomeration growth of semolina to produce couscous grains leads to increasing water  
207 content and decreasing compactness, according to an increase in the median diameters of the  
208 structures ([Barkouti et al., 2014](#); [Bellocq et al., 2017](#); [Rondet et al., 2010](#); [Saad et al., 2011](#)).  
209 In the present study at unique process water content, we observe that the structures obtained  
210 on the different sieves are characterized by the same trend.

211 Taking into consideration the specific shape of the particle distribution curve ([Fig. 2](#)) and the  
212 hydrotextural characteristics ([Fig. 3](#)) of the wet agglomerates of standard semolina, it makes  
213 possible to distinguish different types of structures according to their diameter ([Benali et al.,](#)  
214 [2009](#); [Iveson et al., 2001](#); [Saad et al., 2011](#)). The small structures (diameter  $< 0.5$  mm) are the  
215 "native particles of semolina". Their water content is low and remains always smaller than  
216 the capillary condensation water content (0.21). The small structures can also contain slight  
217 amounts of fragments of the larger structures that could be generated by the mechanical  
218 erosion of larger structures due to the shear stresses during the wet-agglomeration. The  
219 structures called "fragments" (diameter close to 0.55 mm) are obtained by the breakage of the  
220 very large dough pieces due to the mechanical stress during process. The structures called  
221 "nuclei" (diameter between 0.63 and 0.9 mm) are structures obtained by primary association  
222 of the native semolina particles. The structures called "agglomerates" (diameter between 0.9  
223 and 2 mm) are obtained by the association of fragments and/or nuclei. Their water contents  
224 are located between the values of capillary condensation (0.21) and the plastic limit ( $w_p =$   
225 0.59) of durum wheat semolina. The very large structures (with diameter  $> 2.5$  mm) are

226 called "the dough pieces". Their water content is higher than the plastic limit ( $w_p$ ) of the  
227 semolina. The plastic limit is defined as the water content at which the sample maintains any  
228 applied deformation (Atterberg, 1911). The water content is then enough high to ensure their  
229 saturation (Rondet et al., 2013).

230 The weight proportion of these different fractions is presented in Table 2. The amount of the  
231 agglomerates is relatively low (only 27.2%). Similar low values are classically observed  
232 during the wet-agglomeration stage and are typical of the low process efficiency of the  
233 manufacture of the industrial couscous grains (Abecassis et al., 2012).

234

235

### 236 3.2. Influence of the diameter and the span of native particles

237 We investigated the impact of the size characteristics of the native particles, on the wet  
238 agglomeration mechanisms by testing the selected raw materials with different values of  
239 median diameter and/or span (Table 1). Experiments were conducted at similar mean water  
240 content. These selected semolina were characterized by almost constant values of protein  
241 contents (between 12.3 and 13.0%). The wet-agglomeration process generates different  
242 curves of size distribution of the wet agglomerates as depicted in Figure 4. Whatever the  
243 characteristics of the raw materials, the wet structures are characterized by a large diversity in  
244 size and the curve of particle size distribution remain not unimodal.

245 The impacts of the median diameter or of the span on the weight fractions of the different  
246 structures (particles, fragments, nuclei, agglomerates, and dough pieces) are presented in  
247 Table 2. For each experiment, these different structures were also characterized by their water  
248 content and compactness as a function to their diameter (Fig. 5).

249 The impact of the span of the semolina (at similar median diameter) can be described by  
250 comparing the results obtained with the standard semolina and the low span semolina (Table  
251 1). Using these two semolina with different span values (1.51 and 0.92) and almost similar  
252 median diameter (287 and 282  $\mu\text{m}$ ) generates similar wet agglomeration conditions according  
253 to the value of the diameter ratio ( $d_{50\text{semolina}} / d_{50\text{droplet}} = 1.2$ ).

254 The present results demonstrated a significant effect of the span of the semolina on the  
255 weight fractions of the different structures (Table 2). The distributions of the hydrottextural  
256 properties (water content and compactness) as a function of the size are in the same range  
257 (Fig. 5). Besides, the homogenization of the population of native particles around the median  
258 diameter (*i.e.* lower span) seems to lead to a strong decrease of the population of the "small  
259 particles" and of the "fragments" for the benefit of "nuclei" (Table 2). This result suggests

260 that the process of nucleation/growth is favoured. The conditions in which it takes place still  
261 lead to the formation of "dough pieces" and to lower contents of "agglomerates".  
262 The impact of the **median diameter** of the semolina (at almost similar span) can be  
263 investigated at low values of span or at high values of span. The comparison of the small  
264 semolina ( $d_{50} = 129 \mu\text{m}$ ) and the standard semolina ( $d_{50} = 287 \mu\text{m}$ ) is done at similar high  
265 values of span (1.58 and 1.51) (Fig. 4a). The comparison of the results obtained with the low  
266 span semolina ( $d_{50} = 282 \mu\text{m}$ ), the coarse semolina ( $d_{50} = 339 \mu\text{m}$ ), and the very coarse  
267 semolina ( $d_{50} = 393 \mu\text{m}$ ) is done at similar low values of span (0.92, 1.02, and 0.77) (Fig. 4b).  
268 Using these semolina generates very different wet agglomeration conditions, according to  
269 values of the diameter ratio ( $d_{50\text{semolina}} / d_{50\text{droplet}}$ ) with values ranging from 0.5 to 1.6.  
270 The decrease of the  $d_{50}$  of the semolina leads to an increase of the population of  
271 "agglomerates" and to a decrease of the population of "dough pieces". Experiments carried  
272 out using the semolina with the smallest median diameter (small semolina) induced the  
273 disappearance of the population of "fragments" (Table 2). This result suggests that the  
274 process of nucleation/growth seems exclusive. Indeed, when drops of water are larger than  
275 the native particles (ratio  $d_{50\text{semolina}} / d_{50\text{droplet}} = 0.5$ ), the nucleation is essentially controlled by  
276 the size of the drops, which aggregate the particles. The nuclei generated by this way join  
277 themselves and give more compact agglomerates (Fig. 5) with a better yield, as far as the  
278 production of dough pieces is strongly limited. These two different modifications of the  
279 semolina population follow preferentially the nucleation/growth mechanism in comparison to  
280 the mechanisms of dough formation/fragmentation. The ratio  $d_{50\text{semolina}}/d_{50\text{droplet}}$  plays an  
281 important role in the nucleation regime which is here a "drop-controlled" and corresponds to  
282 situation where the drop size controls preferentially the nucleation (Hapgood et al., 2003).  
283 Experiments carried out using the semolina with the largest median diameter (low span  
284 semolina, coarse semolina, and very coarse semolina) were realized at high values of the ratio  
285  $d_{50\text{semolina}}/d_{50\text{droplet}}$  (up to 1). The increase of the diameter of semolina then generates a small  
286 increase in the weight fraction of the "dough pieces". The strongest trend comes from the  
287 increase of the weight fraction of the "fragment" in relation to the decrease of the weight  
288 fraction of the "nuclei". The increases of the weight fractions of "dough pieces" and  
289 "fragments", which have a pasty structure ("fragments" arising from the break of the "dough  
290 pieces"), induce lower compactness and higher water content than the other configurations  
291 (Fig. 5). These results indicate that the process leads to a higher heterogeneity in the  
292 agglomerated structures, due to the increase in the median diameters of the native particles.  
293

294

### 295 *3.3. Influence of the protein content of semolina*

296 We investigated the impact of the protein content (between 7.7 and 13.8%) of the native  
297 semolina on the wet agglomeration mechanisms by comparing three raw materials (Table 1).  
298 The experiments were conducted at similar mean water content ( $\bar{w} = 0.44$ ) and at almost  
299 similar values of median diameter (227 to 262  $\mu\text{m}$ ) and span (1.25 to 1.13) of semolina. The  
300 wet agglomeration process generates different curves of the size distribution of the wet  
301 agglomerates as depicted in Figure 6. Whatever the protein content, the wet agglomerates are  
302 characterized by a large diversity in size, and the curve of particle size distribution remain not  
303 unimodal.

304 The impacts of the protein content of the native semolina on the weight fractions of the  
305 different structures (small, fragments, nuclei, agglomerates, and dough pieces) are presented  
306 in Table 2. For each experiment, the different structures are also characterized by their water  
307 content and compactness as a function to their diameter (Fig. 7).

308 We observe a slight difference in the particle size distribution curve obtained with the three  
309 native semolina, which have different protein content (Fig. 6). The weight fractions of each  
310 wet structures remain very close to each other using the very low, low and high protein  
311 contents semolina. The hydrotextural characteristics of the wet structures (Fig. 7) are also  
312 similar as a function of the values of protein content of the native semolina. We can note that  
313 the high protein semolina slightly favours the population of "nuclei" and "agglomerates".  
314 "Fragments" are almost inexistent and the amount of "dough pieces" is slightly lower by  
315 using the high protein semolina. This result suggests that the process of fragmentation is  
316 restricted. These effects could be explained by the fact that proteins would promote semolina  
317 particles stickiness and limit the process of fragmentation. Nevertheless, changes in the  
318 protein content of semolina do not appear to have a significant influence on wet  
319 agglomeration mechanisms and the contribution of biochemical mechanisms does not  
320 therefore appear to be dominant.

321

## 322 4. Discussion

323

### 324 4.1. Mechanisms of the wet-agglomeration of semolina

325 By reporting on a hydrotextral diagram all the experimental values of water content and  
326 compactness for the different structures produced by the wet-agglomeration process (Fig. 8),  
327 we observe that structures on each sieve follow the saturation curve (Ruiz et al., 2011). For  
328 each structure, the saturation degree is equal to 1.

329 Figure 9 depicts the hydrotextral diagram of the wet-agglomerates obtained for the  
330 experiments using the different semolina. Results show that the different collected structures  
331 also follow the saturation curve, which means that the saturation degree is equal to 1.  
332 Changing the size characteristics of semolina or the protein content of semolina does not  
333 change the position of the experimental data on the saturation curve.

334 The present work demonstrates that the mechanisms leading to these agglomerated structures  
335 are different from these found in previous studies. As described by Saad et al., (2011), an  
336 agglomeration mechanism of nucleation/growing takes place, but mechanisms of dough  
337 formation/fragmentation are also observed (Iveson et al., 2001).

338 Previous works in semolina agglomeration highlighted that the follow-up of both the textural  
339 and characteristic length (i.e. the diameter) of agglomerates allowed us identifying a fractal  
340 morphogenesis process (Barkouti et al., 2014; Rondet et al., 2010). The suggested model

341 describing fractal growth of agglomerates can be written as:  $\phi = \phi_N \left(\frac{d_{50}}{d_N}\right)^{Df-3}$ , where  $Df$

342 was the fractal dimension of the generated agglomerates;  $d_{50}$  was the median diameter of the  
343 agglomerate population,  $\phi_N$  and  $d_{50N}$  were respectively the solid volume fraction and the  
344 median diameter of the nuclei (Rondet et al., 2010). Fractal structure of agglomerates  
345 elaborated by a wet agglomeration process had ever been highlighted (Pashminehazar et al.,  
346 2016; Turchiuli and Castillo-Castaneda, 2009). In the case of a fractal growth, this particular  
347 process involves nuclei association by homothetic scale up, where nuclei constitute the  
348 elementary structure of the generated agglomerates. Nuclei were identified after sieving and  
349 optical microscopy observations. Their median diameter and solid volume fraction were  
350 determined. This analyse is purposed to characterise the agglomerates.

351 Because small range of water contents has been explored, the present data are not completely  
352 related to growing mechanisms. The fractal dimension had been calculated:  $Df \sim 3$ . This  
353 value, which is an integer, is the fact of saturation. It indicates that agglomerate could be  
354 assimilated to geometrical structures in which nuclei do not play the role of a base unit.

355 The agglomeration mechanism of nucleation/growth, which takes place here, occurs in three  
356 major stages. (i) The nucleation stage is both depending on wetting/mixing parameters with  
357 physicochemical properties of fluid and surface particle (Ax et al., 2008; Chouk et al., 2009;  
358 Iveson et al., 2001). (ii) The growing stage could be described as the formation of large  
359 grains by the association of several nuclei following a fractal morphogenesis (Rondet et al.,  
360 2010; Saad et al., 2011). (iii) The “pasting” stage occurs by adding water and leads to the  
361 transformation of the agglomerates in dough pieces through percolation (Rondet et al., 2013;  
362 Ruiz et al., 2011). The transformation of agglomerates in dough structures results in a  
363 considerable increase in grain size and biochemical changes with the formation of partial  
364 dough structures involving the proteins inside the grains. The percolation mechanisms could  
365 be described as the formation of very large structures by hydration and adhesion. It can be  
366 associated with a mechanical deformation of large agglomerates to generate some dough  
367 pieces, when the water content is close to the plastic limit. The compactness of the dough  
368 pieces is smaller than that of agglomerates and nuclei (Fig. 8). These structures could exhibit  
369 stronger strain, and when they are maintained in condition of agitation within a bed of more  
370 compact particles, is going to favour their disintegration. This situation takes place generally  
371 in high shear mixer conditions, where the shear stress field does not allow the stability of  
372 dough (Iveson et al., 2001). The breakage mechanisms generate small-sized fragments, which  
373 are strengthened as observed on the size distribution curve (Fig. 2). Besides their slightly  
374 lower size, the difference with nuclei comes because having been very hydrated, they have a  
375 dough texture, whereas nuclei is made by associations of semolina particles. Fragments have  
376 lower water content and higher compactness than dough pieces, due to the strengthening of  
377 their structure during the mechanical agitation. As explained by Wade et al. (Wade et al.,  
378 2015) and Rondet et al. (Rondet et al., 2016), the breakage mechanism of dough pieces is  
379 able to generate granules with high intragranular compactness, due to the complete filling of  
380 intra-particle pores by the binder liquid, but the addition of further powders can reduce the  
381 liquid saturation of the granules. So generated, fragments can interact with nuclei and  
382 contribute to build agglomerates with the same growing mechanism as ever described. This  
383 paste/fragmentation mechanism could be compared to a nucleation by downsizing, by  
384 difference with the "classic" nucleation, which is a bottom-up mechanism (Iveson et al.,  
385 2001). We can notice that this phenomenon could be totally developed in low shear mixer to  
386 generate agglomerates (Rondet et al., 2016). In the case of this study, the spray process  
387 conditions associated to mixing process conditions generate a very significant population of

388 dough pieces (Fig. 2). It occurs here a concomitant paste/fragmentation mechanism, which  
389 generates fragments, associated to nuclei in the growing process.

390 As mentioned in Barkouti et al. (2014), to identify the major mechanisms contributing to the  
391 structure layout during the growing stage, it seems interesting to combine the fluctuations of  
392 water content and compactness standard deviations. Figure 10 shows that for all the  
393 structures considered fluctuations of compactness and water content are correlated, whatever  
394 the semolina used as raw materials. Indeed, if the different types of structures (discriminated  
395 by size, water content, and compactness) are interacting by binding, the fluctuations of  
396 hydrotexural values would be independent. Nuclei and fragments contribute to the primary  
397 step of growing. Then, the correlation results can be interpreted as the fact that the  
398 agglomerates grow thanks to the association of structures that belong to the same category in  
399 terms of hydro-textural characteristics. As hydrotexural properties are related to structural  
400 size, the association law is based on an association by both size-class. However, as ever  
401 mentioned, the structures are poorly fractal.

402

403

#### 404 4.2. Specification of durum wheat semolina for wet agglomeration

405 The present results allow proposing some specifications for the durum semolina used for the  
406 production of the couscous grains by the wet agglomeration process. The protein content  
407 does not appear to be a significant factor impacting the wet agglomeration mechanisms. We  
408 have only observed slight changes in the wet agglomeration process when using semolina  
409 between 7.7% and 13.8% protein content. It was thus not possible to define a specification of  
410 the protein content to control the wet agglomeration mechanisms. This work will have to be  
411 completed by investigating the impact of the protein content of semolina on the final quality  
412 of the couscous grains.

413 On the other hand, the size characteristics of the native semolina significantly affect the wet  
414 agglomeration mechanisms. Changing the median diameter or the span of the native semolina  
415 generates large impact of the agglomeration yields. The higher amount of the fraction of  
416 agglomerates with diameter ranging between 1 and 2 mm was obtained when using semolina  
417 with low median diameter and low span. Additional work will be conducted to evaluate the  
418 impact on the final quality of the couscous grains.

419

420

## 421 **5. Conclusion**

422

423 This work deals with the study of the impact of particle-size distribution and protein content  
424 characteristics of semolina on the wet agglomeration process. The results demonstrate that  
425 the span and the median diameter of the native powder have a significant influence. As the  
426 median diameter increases, the ratio of the dough pieces and fragments in the bed increases  
427 and the ratio of nuclei and agglomerates decreases. The impact of the protein content is  
428 lower. The different structures generated by the agglomeration process result from two major  
429 modes of agglomeration: nucleation/growing and dough formation/fragmentation. We show  
430 that structures as nuclei or fragments could be individually identify because they differ  
431 essentially from their hydrottextural properties. An increase in the amount of dough pieces  
432 leads to an increase in the fragments and an increase of the polydispersity of the structures.  
433 The configuration leading to the higher amount of the agglomerates population corresponds  
434 to the low diameter semolina. The relative size of native particles is the major parameter to  
435 modulate the formation of the fragments. In the same way, semolina with higher protein  
436 content could strengthen the structure by favouring the stickiness between the semolina  
437 particles. The process of fragmentation is limited and the ratio of fragment in the bed  
438 decreases.

439

## 440 **ACKNOWLEDGEMENTS**

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444 DUR.

445

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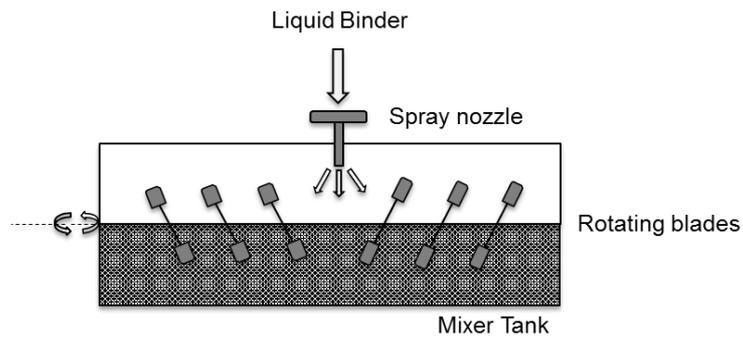
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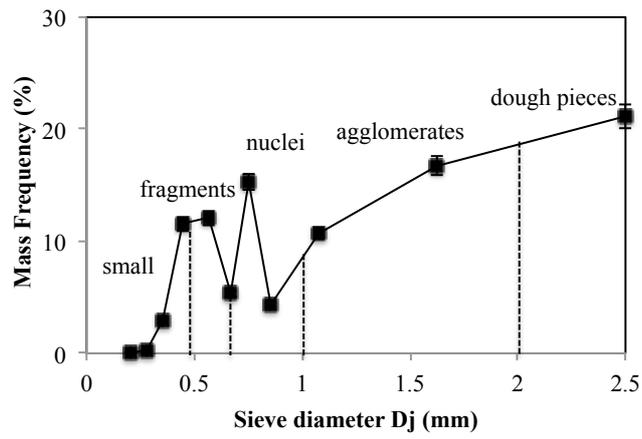
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Fig. 1. Sketch of the horizontal low shear mixer equipment.

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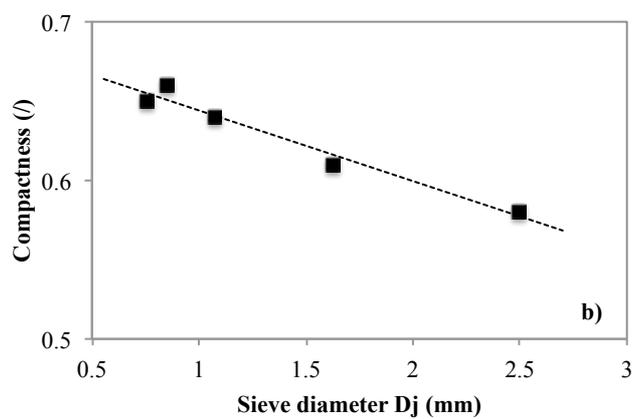
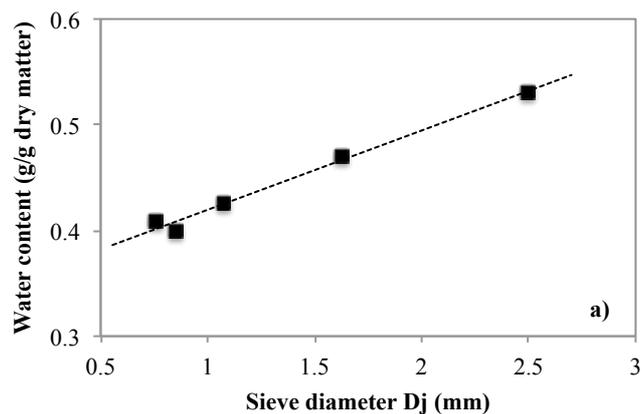
**Fig. 2.** Distribution curve of the weight fractions as a function of the diameters of the wet agglomerates produced by the wet-agglomeration process of standard semolina.

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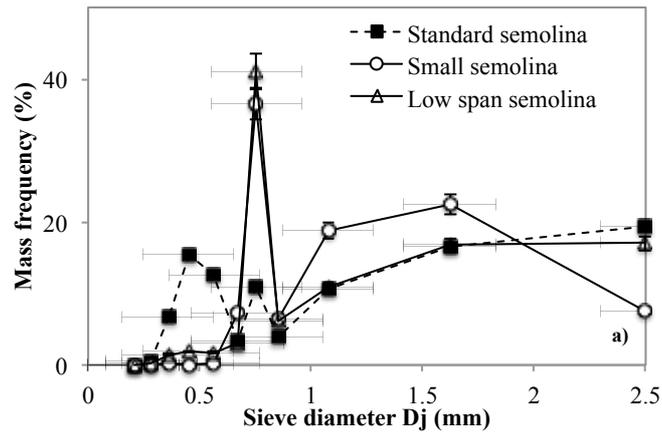
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12 **Fig. 3.** Distribution curves of the measured values of water content (a) and compactness (b), as a function of the  
13 diameter of the structures produced by the wet-agglomeration process of standard semolina.

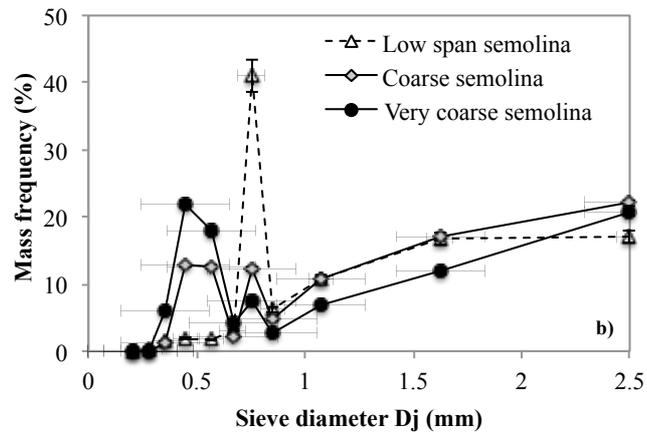
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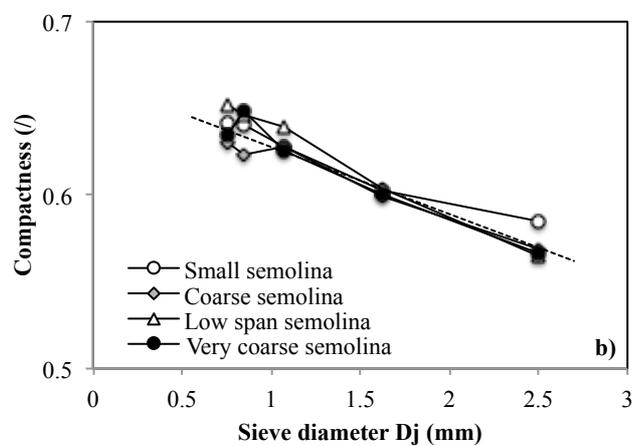
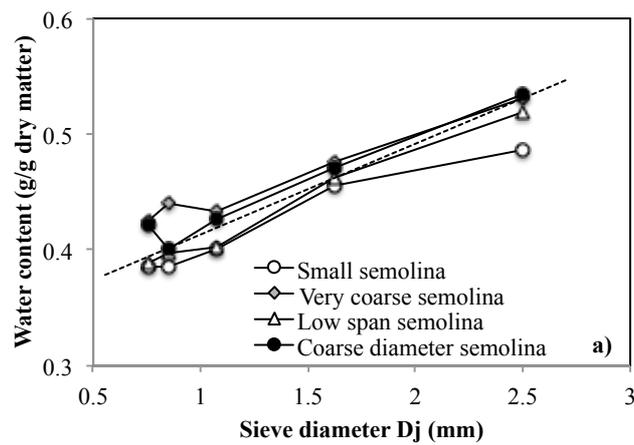


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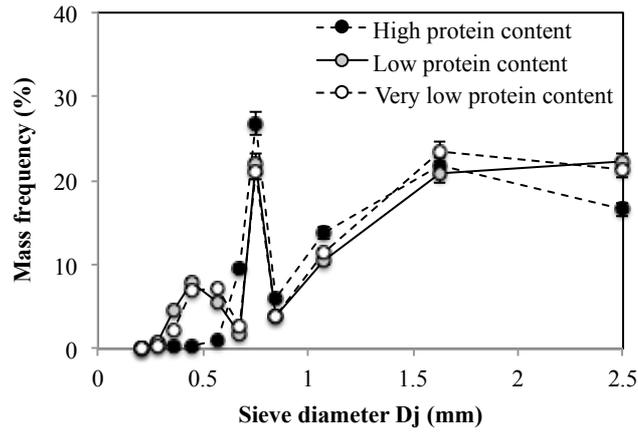


18 **Fig. 4.** Impact of the (a) median diameter at constant span (small semolina) and the span at constant median  
 19 diameter (low span semolina) and (b) of the median diameter (at constant span) of the native semolina, on the  
 20 distribution curves of the weight fractions as a function of the diameters of the wet agglomerates produced by  
 21 the wet-agglomeration process.

22



26 **Fig. 5.** Impact of the median diameter or diameter span of the native semolina on the distribution curves of the  
 27 measured values of water content (a) and compactness (b), as a function of the diameter of the wet agglomerates  
 28 produced by the wet-agglomeration process of different semolina. The dotted line is the value of the standard  
 29 semolina.  
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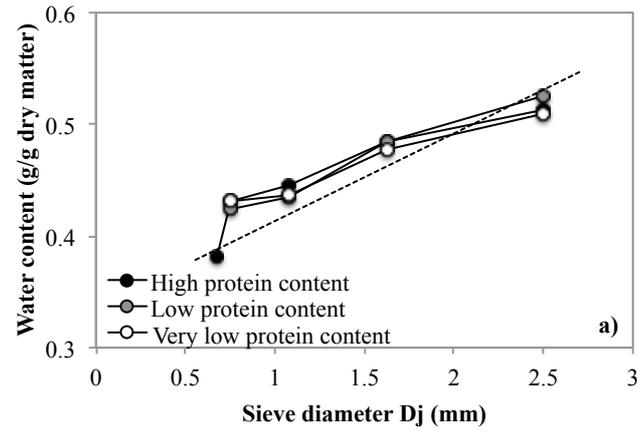


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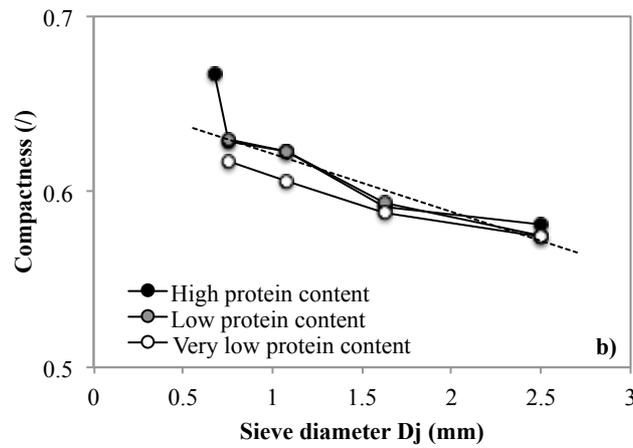
32 **Fig. 6.** Impact of the protein content of the native semolina on the distribution curves of the weight fractions as a  
 33 function of the diameters of the wet agglomerates produced by the wet-agglomeration process.

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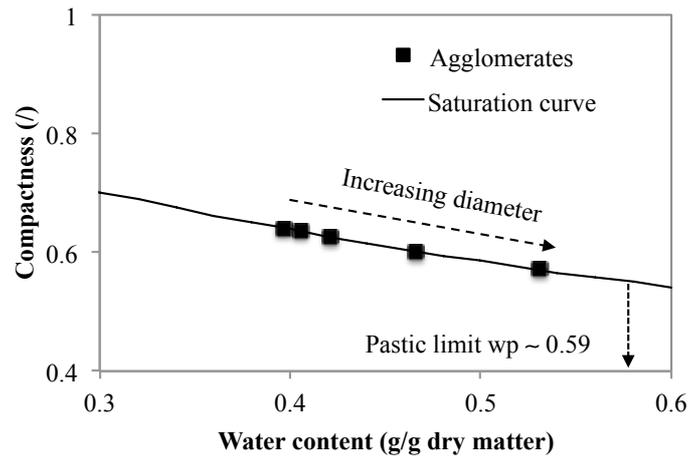


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37 **Fig. 7.** Impact of the protein content of the native semolina on the distribution curves of the measured values of  
 38 water content (a) and compactness (b), as a function of the diameter of the wet agglomerates produced by the  
 39 wet-agglomeration process of different semolina. The dotted line is the value of the standard semolina.

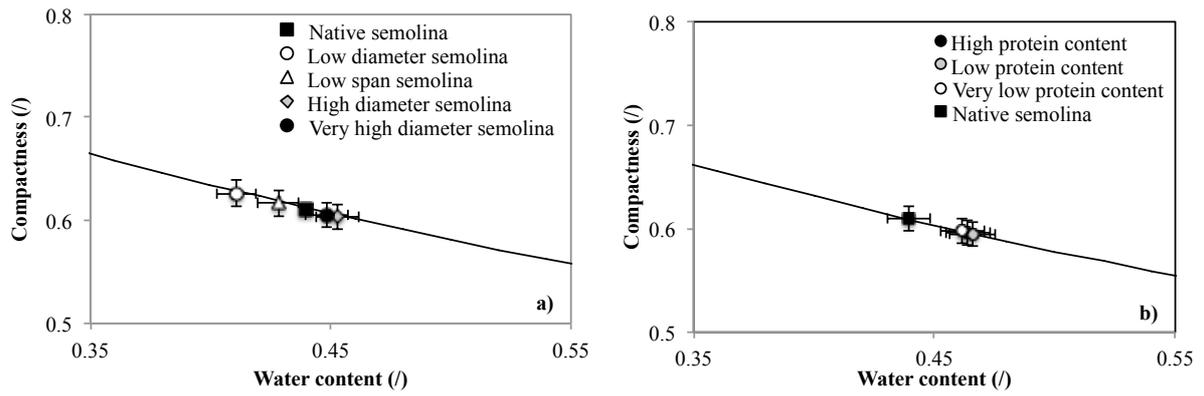
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42 **Fig. 8.** Hydrotextural diagram of the different structures collected on each sieve after the wet agglomeration of  
 43 standard semolina.  
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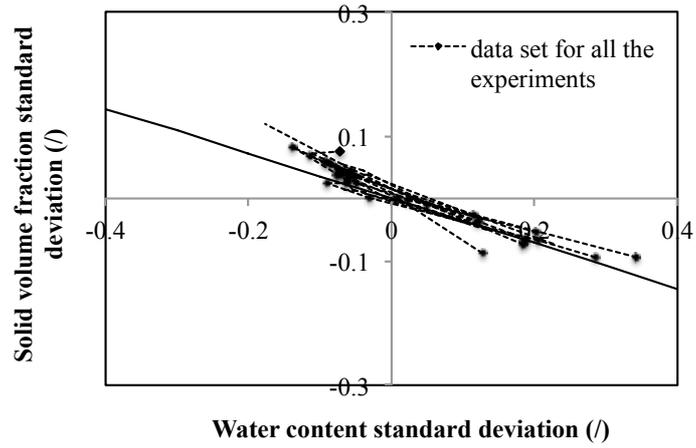
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**Fig. 9.** Hydrotextural diagram of the different structures collected on each sieve after the wet agglomeration of semolina with different size distributions (a) or with different protein contents (b).

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**Fig. 10.** Variations of compactness standard deviation of agglomerates according to water content standard deviation for all trials.

## 1 **Figure captions**

2

3 **Fig. 1.** Sketch of the horizontal low shear mixer equipment.

4

5 **Fig. 2.** Distribution curve of the weight fractions as a function of the diameters of the wet agglomerates  
6 produced by the wet-agglomeration process of standard semolina.

7

8 **Fig. 3.** Distribution curves of the measured values of water content (a) and compactness (b), as a function of the  
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10

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23

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34 **Fig. 10.** Variations of compactness standard deviation of agglomerates according to water content standard  
35 deviation for all trials.

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1 **Table 1**

2 Physical and biochemical characteristics of the different selected durum wheat semolina.

	$d_{50}$ ( $\mu\text{m}$ )	Span (/)	True density ( $\rho_s^*$ ) ( $\text{g}/\text{cm}^3$ )	Water content ( $\text{g}/\text{g}$ dry matter)	Proteins content ( $\text{g}/100$ g dry matter)
Standard semolina	287 ( $\pm 2$ ) <sup>f</sup>	1.51 (+/- 0.01) <sup>f</sup>	1.415 ( $\pm 0.003$ ) <sup>a</sup>	0.173 ( $\pm 0.001$ ) <sup>d</sup>	12.4 ( $\pm 0.1$ ) <sup>c</sup>
Low span semolina	282 ( $\pm 2$ ) <sup>e</sup>	0.92 (+/- 0.04) <sup>b</sup>	1.447 ( $\pm 0.004$ ) <sup>b</sup>	0.160 ( $\pm 0.004$ ) <sup>bc</sup>	12.7 ( $\pm 0.1$ ) <sup>d</sup>
Small semolina	129 ( $\pm 1$ ) <sup>a</sup>	1.58 (+/- 0.02) <sup>g</sup>	1.461 ( $\pm 0.003$ ) <sup>c</sup>	0.157 ( $\pm 0.001$ ) <sup>b</sup>	13.0 ( $\pm 0.1$ ) <sup>e</sup>
Coarse semolina	339 ( $\pm 2$ ) <sup>g</sup>	1.02 (+/- 0.01) <sup>c</sup>	1.451 ( $\pm 0.006$ ) <sup>b</sup>	0.139 ( $\pm 0.001$ ) <sup>a</sup>	12.4 ( $\pm 0.2$ ) <sup>cd</sup>
Very coarse semolina	393 ( $\pm 1$ ) <sup>h</sup>	0.77 (+/- 0.00) <sup>a</sup>	1.453 ( $\pm 0.002$ ) <sup>bc</sup>	0.161 ( $\pm 0.001$ ) <sup>c</sup>	12.3 ( $\pm 0.1$ ) <sup>c</sup>
Very low protein semolina	227 ( $\pm 3$ ) <sup>b</sup>	1.13 (+/- 0.02) <sup>d</sup>	1.462 ( $\pm 0.003$ ) <sup>c</sup>	0.178 ( $\pm 0.001$ ) <sup>ef</sup>	7.7 ( $\pm 0.1$ ) <sup>a</sup>
Low protein semolina	234 ( $\pm 3$ ) <sup>c</sup>	1.14 (+/- 0.02) <sup>d</sup>	1.448 ( $\pm 0.003$ ) <sup>b</sup>	0.177 ( $\pm 0.001$ ) <sup>e</sup>	9.4 ( $\pm 0.1$ ) <sup>b</sup>
High protein semolina	262 ( $\pm 3$ ) <sup>d</sup>	1.25 (+/- 0.02) <sup>e</sup>	1.458 ( $\pm 0.003$ ) <sup>c</sup>	0.180 ( $\pm 0.001$ ) <sup>f</sup>	13.8 ( $\pm 0.1$ ) <sup>f</sup>

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4 Values are means ( $\pm$  standard deviation).5 Values in column with the same letter were not significantly different ( $P < 0.05$ ).

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8 **Table 2**

9 Impact of the characteristics of the native semolina on the weight fractions of the different structures produced  
 10 during the wet agglomeration process.

	Weight fractions of the different structures after agglomeration				
	Small	Fragments	Nuclei	Agglomerates	Dough pieces
Standard semolina	22.7 ( $\pm$ 1.5) <sup>e</sup>	12.5 ( $\pm$ 2.0) <sup>d</sup>	10.9 ( $\pm$ 10.6) <sup>abc</sup>	27.2 ( $\pm$ 0.3) <sup>b</sup>	19.3 ( $\pm$ 2.2) <sup>bcd</sup>
Small semolina	0.3 ( $\pm$ 1.2) <sup>a</sup>	0.3 ( $\pm$ 2.6) <sup>a</sup>	36.5 ( $\pm$ 4.9) <sup>e</sup>	41.1 ( $\pm$ 3.6) <sup>e</sup>	7.6 ( $\pm$ 1.4) <sup>a</sup>
Low span semolina	3.7 ( $\pm$ 1.0) <sup>b</sup>	1.7 ( $\pm$ 0.8) <sup>a</sup>	41.0 ( $\pm$ 26.0) <sup>cde</sup>	27.6 ( $\pm$ 3.4) <sup>bc</sup>	17.0 ( $\pm$ 1.7) <sup>bc</sup>
Coarse semolina	13.9 ( $\pm$ 0.5) <sup>d</sup>	12.6 ( $\pm$ 6.5) <sup>cde</sup>	12.2 ( $\pm$ 1.0) <sup>b</sup>	27.9 ( $\pm$ 2.6) <sup>bc</sup>	22.1 ( $\pm$ 2.0) <sup>d</sup>
Very coarse semolina	28.0 ( $\pm$ 0.4) <sup>f</sup>	18.1 ( $\pm$ 0.0) <sup>e</sup>	7.4 ( $\pm$ 0.2) <sup>a</sup>	18.8 ( $\pm$ 0.3) <sup>a</sup>	20.6 ( $\pm$ 1.9) <sup>cd</sup>
Very low protein semolina	9.5 ( $\pm$ 0.1) <sup>c</sup>	7.3 ( $\pm$ 0.4) <sup>c</sup>	21.1 ( $\pm$ 1.1) <sup>c</sup>	34.8 ( $\pm$ 0.9) <sup>d</sup>	21.5 ( $\pm$ 1.1) <sup>d</sup>
Low protein semolina	13.2 ( $\pm$ 0.2) <sup>d</sup>	5.6 ( $\pm$ 0.3) <sup>b</sup>	22.1 ( $\pm$ 1.1) <sup>c</sup>	31.3 ( $\pm$ 0.8) <sup>c</sup>	22.2 ( $\pm$ 1.1) <sup>d</sup>
High protein semolina	1.3 ( $\pm$ 1.6) <sup>ab</sup>	1.1 ( $\pm$ 0.1) <sup>a</sup>	26.8 ( $\pm$ 1.3) <sup>d</sup>	35.4 ( $\pm$ 0.9) <sup>d</sup>	16.6 ( $\pm$ 0.8) <sup>b</sup>

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12

13 Values are means ( $\pm$  standard deviation).14 Values in column with the same letter were not significantly different ( $P < 0.05$ ).

15