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From printability to palatability: A sensory and hedonic study of 3D-printed cereal- and legume-based products

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Highlights

- Sensory perceptions and liking were mainly affected by the type of flour used.
- Soy-based products were harder, grainier and with a stronger cereal aroma.
- Rye and wheat-based products were sweeter, moister, and more deformable.
- Wheat-based 3D printed products were the most preferred by consumers.
- Rye and soy flour showed great potential for mixed formulations with wheat flour.

Abstract

This study focused on generating formulas with high 3D-printability, nutritious values and appreciated by consumers. Earlier studies developed a thermomechanical treatment to make wheat flour printable, which was then optimized for rye and soy flours to vary the nutritional composition of the printed products, in particular their protein and fiber content. However, few studies have looked at consumers' sensory perceptions and preferences towards printed products. In this study, recipes based on wheat, rye or soy flour were taste-enhanced by the addition of cinnamon and apple puree. A sensory and hedonic characterization approach was then implemented to better understand the sensory criteria associated with each of these flours. By evaluating 7 products with two descriptive methods, we found that rye-based products are less compact and with cinnamon smell moderately pronounced. Soy-based products have less deformation, they are more compact and grainier with less sweetness. Wheat-based products are less hard, more humid, moderately compact and have a stronger cinnamon smell. Hedonic evaluation showed that soy products have the best visual appreciation but the worst textural appreciation. By using PREFMAP method combining sensory description by panelists and hedonic evaluation, we noticed that wheat flour products are consumers favorite (80-95%), followed by rye (35-50%) and soy (10-20%). There is little difference in appreciation of products with or without apple puree (< 10%). This approach provides sensory and hedonic information that will be crucial in establishing a reasoned approach to flour blend formulation in a future study.

Keywords :

3D food printing, cereal, legume, sensory analysis, consumer appreciation

36 1. Introduction

37

38 3D food printing is an emerging technology that offers new possibilities for personalized nutrition,
39 culinary innovation, and sustainable food production. By allowing the precise layering of ingredients,
40 this technology has the potential to be applied in various sectors, from customized meal plans in
41 healthcare to novel food experiences in high-end restaurants. To date, some of the most commonly
42 printed foods include chocolate (Mantihal et al., 2019; Rando & Ramaioli, 2021), gels system (Chen
43 et al., 2021; Sartori et al., 2023), pureed foods (Armstrong et al., 2022; Hassan et al., 2024; Pant et al.,
44 2021) and various starch-based structures such as wheat, rice, potatoes, etc. (Tang et al., 2024). One
45 of the main constraints in food 3D printing is the formulation of printable materials. These materials
46 must exhibit specific rheological properties to ensure smooth extrusion, structural stability, and layer-
47 by-layer adhesion (Godoi et al., 2016; Nijdam et al., 2021). Achieving this requires the right balance
48 between solid and liquid components, which can often conflict with nutritional goals. For example,
49 adding fibers may enhance the healthiness of a product, but this modification can have a negative
50 impact on printability and alter sensory properties such as texture (Keerthana et al., 2020; Krishnaraj
51 et al., 2019; Lille et al., 2018). Thus, designing recipes that are both printable and nutritious while
52 appealing to consumers is a complex challenge.

53 The development of 3D-printed foods from cereals such as wheat is being widely studied, as it
54 enables the generation of different products with a wide range of textures and can be adapted for both
55 sweet and savory foods. These include cookies, snacks, bread, pizza which are popular due to their
56 simple formulation and wide consumer acceptance (Lipton et al., 2015; Pulatsu et al., 2020; Severini
57 et al., 2018). For example, 3D-printed pizza dough has been explored for applications in space travel,
58 where fresh, customizable food is essential for long missions (Santhoshkumar et al., 2024). Similarly,
59 bread and crackers have been printed for use in healthcare settings, particularly for patients with
60 dysphagia who require modified textures (Hemsley et al., 2019; Mirazimi et al., 2022; Sun et al.,
61 2015). The most of these previous studies are focused on wheat-based recipes and a few of other
62 cereal-based recipes or recipes rich in starch. These printed products offer a reliable texture and
63 structural integrity, making them ideal candidates for 3D printing. For wheat flour, a
64 thermomechanical process during dough treatment in 3D printing allows the starch granules to swell
65 and gluten protein to form a continuous closely-packed network embedding swollen starch granules.
66 This structure gives a good viscoelastic property and stickiness to the dough, which are important for
67 the extrudability, adhesion inter-layers and the maintenance of the form in 3D printed products
68 (Masbernat et al., 2021). Whatever the matrix based on, starch and gluten are important components
69 thanks to their water holding capacity. When the gluten is partially replaced by other hydrophobic
70 proteins such as mealworm powder, the water holding capacity of the dough could be influenced,
71 reducing the viscosity of the dough (Pérez et al., 2019). Similar phenomenon can also appear on
72 recipes with cereal without gluten. For example, for rice flour having other proteins than gluten and

73 for tapioca flour containing nearly no proteins, the texture of printed products is more fragile and
74 fluid. But this problem can be corrected by adding hydrocolloids or adjusting water, sugar and lipid
75 content in the dough as rice and tapioca flour are at least both rich in starch (Pulatsu et al., 2020).
76 These mechanisms make starch-rich cereals frequently used in 3D printing studies. However, despite
77 the versatility of starch-rich cereal-based recipes, challenges remain in ensuring the nutritional quality
78 of these products without compromising their printability, texture, sensory appeal and consumer
79 acceptance.

80 Some studies are also looking at the printing of cereal- or legume-based foods with little or no starch,
81 and offering different nutritional benefits (Auyeskhan et al., 2023; Keerthana et al., 2020; Krishnaraj
82 et al., 2019; Lille et al., 2020; Pulatsu et al., 2020). For example, in our previous study (Guénard-
83 Lampron et al., 2023), 25 flours of cereal, pseudo cereal, legume, nut and root categories were
84 screened and compared by HAC and PCA methods. After a first selection with starch, protein, fiber,
85 calcium, ash and several vitamins' contents, 5 flours (rye, chestnut, soy, lupine, chickpea) were
86 selected. A second selection with textural and sensorial observation allowed the final choice of soy
87 and rye flour thanks to their relatively good sensorial perception compared to the other 3 flours. Then
88 with an experimental design based on 10 trials, optimized formulation and thermomechanical
89 treatment parameters were calculated and validated, proving that these two nutritious flours allow a
90 good printing quality. Despite these advancements, there is still limited research on how 3D-printed
91 foods are perceived by consumers, particularly in terms of sensory attributes such as taste, texture,
92 and visual appeal. Most studies to date have focused on the technical aspects of printability and
93 nutrition, placing less emphasis on the importance of consumer experience (Čukelj Mustač et al.,
94 2023). In several recent studies, different ingredients were tested in 3D printing dough formulation,
95 such as wheat and amaranth bran, but the sensorial perception of these formulations were limited in
96 the publications, and the intensity of each descriptor were not always associated to hedonic evaluation
97 and consumer acceptability or vice versa, or without comparison with a control recipe (Habuš et al.,
98 2022; Keerthana et al., 2020; Krishnaraj et al., 2019; Lille et al., 2020). Yet, for 3D-printed foods to
99 gain widespread acceptance, it is crucial to design matrices that not only meet health and technical
100 requirements but also satisfy consumer preferences. In the case of soy flour and rye flour which were
101 validated for their printability (Guénard-Lampron et al., 2023), soy flour is known to be rich in
102 proteins and essential amino acids, offers significant nutritional benefits, particularly for vegetarian or
103 vegan diets. It is also a valuable source of vitamins and minerals such as iron and calcium. However,
104 soy-based products often face sensory barriers such as beany flavors or gritty textures, which can
105 deter consumer acceptance, especially in European countries where soy-based foods are less
106 embodied in the culture than in Asian area (Mirazimi et al., 2023; Shin et al., 2013; Tu, 2010). Rye
107 flour, known for its high fiber content and beneficial bioactive compounds like lignans, poses similar
108 challenges. These sensory drawbacks must be addressed to increase consumer appreciation of such
109 nutritious ingredients.

110 Thus, this study aims to fill this gap by investigating the sensory properties of three different flours
111 (wheat, soy, and rye) used in 3D food printing. Each flour has unique nutritional profiles and sensory
112 characteristics that may influence their performance in 3D printing and their acceptance by
113 consumers. By exploring the relationship between these flours, their printability, and sensory
114 attributes, this research seeks to develop new strategies for creating printable foods that align with
115 consumer expectations for taste, texture, and visual appeal.

116 2. Material and Methods

117 2.1. Ingredients and preparation of the printable dough

118 The three flours used in this study were: rye flour (Type 170, Moulins de Versailles, France), soy
119 flour (toasted and whole type, Alnatura, Germany) and wheat flour (Type 55, Villa Bleue, Minoterie
120 Bourseau, France). The choice of using these 3 flours is linked to our previous study (Guénard-
121 Lampron et al., 2023), in which soy, rye, lupin, chestnut and chickpea were selected in a first
122 screening step with nutritional, economic and ecological criteria. Then, only soy and rye were retained
123 after printability pre-tests for having better texture and sensory characteristics. Also, legumes are not
124 commonly used in bread-type products, but the more and more legume-based products such as lupine,
125 pea, chickpea and soy-based ingredients start to be widely used for their protein high content (Aslan
126 & Bilgiçli, 2022; Halm et al., 2024). Soybean flour is also already used in the preparation of certain
127 cakes (Sanful et al., 2010; Sedem Dzah et al., 2016; Ugwuona et al., 2012) which shows the interest in
128 working with these flours.

129 Tap water, cinnamon (Ducros, France) and apple puree without added sugar (Cora, France) were also
130 used to prepare the doughs from these flours. The water content (Table 1) of apple puree was
131 determined by weighing the dried matter after 5 h at 103°C (Etuve EM10, Chopin Technologies,
132 Villeneuve-la-Garenne, France) and a reference method for cereals-based products (NF V03-707) was
133 used for the other ingredients.

134 **Table 1**

135 Water content measured for each ingredient.

	Rye (T170)	Soy	Wheat (T55)	Apple puree	Cinnamon
Water content (%)	11.2 ± 0.2	7.4 ± 0.1	9.5 ± 0.1	87.7 ± 0.1	11.8 ± 0.1

136

137 Doughs made with wheat flour were prepared as described by (Guénard-Lampron et al., 2021) using
138 the same total water content (65 % w/w). A planetary mixer with a leaf device (KSS45 EOB
139 CLASSIC, KitchenAid, USA) was used for the mechanical treatment (120 rpm, 12 min) and then a
140 multifunction robot (Vorwerk, Thermomix TM6, FR) for the thermomechanical treatment (85°C, 100
141 rpm, 15 min). Doughs made with rye or soy flour were prepared according to the process parameters
142 optimized (water content: 59 % for soy and 60 % for rye, thermomechanical treatment: 27 for soy and

143 22 min for rye) previously (Guénard-Lampron et al., 2023). To adapt these recipes for sensory
144 analysis, a consumer survey was conducted with 21 participants. Cinnamon flavor was chosen from
145 among eight sweet flavors and a ninth "no flavor" option. Its quantity was then determined at 2% with
146 preliminary trials and the result of hedonic appreciation of 20 consumers combined with the result of
147 another profile analysis (not described in this study) and reverses-engineering method. Meanwhile, to
148 enhance the sensory experience, the addition of 20% apple puree was chosen because it has the least
149 impact on dough viscosity among 5 vegetable and fruit purees tested. Additionally, it lowers the mean
150 force of the dough in back extrusion compared to other purees (celery, broccoli, carrot or mango) and
151 may help soften soy-based products, improving texture perception (Masbernat, 2021). Thus, in this
152 study, each dough was flavored with 2 % (w/w) cinnamon and a version with 20% (w/w) apple puree
153 for each flour was prepared. After preparation and cooling, the doughs were kept at 4°C overnight.

154 2.2. Texture analysis of printable dough

155 A texture analysis of each dough at room temperature was performed (Guénard-Lampron et al., 2023).
156 The mean force (N) was measured between 10 and 20 s of the back extrusion method (piston probe
157 with annulus gap of 1.5 mm, crosshead speed of 1mm/s, 30 mm of depth) using a texture analyzer
158 (TaHD, Stable Micro Systems, Surrey, UK). Triplicate were realized for each formulation (after
159 dough preparation and after overnight storage at 4°C) to determine the average firmness of the
160 doughs.

161 2.3. Printing and baking

162 The 3D food printer prototype built by Dagoma (Roubaix, France) was used in our study (Guénard-
163 Lampron et al., 2021, 2023b; Masbernat, 2021). The day after the dough was produced, it was
164 poached in the syringe of the prototype and was printed (20 ± 1 °C) on silicone baking mat. Printing
165 and baking parameters were determined by preliminary tests and fixed for all printed products. We
166 used a nozzle diameter of 3.4 mm, a filling rate of 55 % and a printing speed of 10 mm.s^{-1} to print six
167 cylindrical model (diameter: 3 cm, height: 1.5 cm) for each batch of dough. 3D-printed products were
168 then baked at 175 ± 5 °C during 17 min directly after the printing. Oven baking time and temperature
169 were determined during preliminary tests after assessing the general appreciation of 10 products
170 among 20 consumers. The percentage of water loss was measured by comparing the mass of printed
171 products before and after baking.

172 2.4. Experimental design

173 A full factorial design was used to study two factors: the type of flour (wheat, rye or soy) and the
174 apple puree (0 or 20%) leading to the production of 6 different products (Table 2). However, in order
175 to check the reliability of the panelists and consumers assessments, a duplicate product based on
176 wheat flour and without apple puree was generated.

177 2.5. Sensory analysis

178 This study was carried out in accordance with the international ethical guidelines for research
 179 involving humans established in the Declaration of Helsinki. A longstanding internal code of conduct
 180 for sensory science has also been respected.

181 Two descriptive methods (description by panelists and then by consumers) and a hedonic test were
 182 carried out. Four panelists experienced in evaluating cereal- and legume-based printed products and
 183 used to participating in sensory analysis were recruited to describe the products. 56 consumers were
 184 recruited to evaluate the products at home, using an online questionnaire including hedonic and
 185 CATA tests. These consumers were recruited via email invitations from the school network, with an
 186 exclusion criterion based on gluten and soy allergies. The inclusion criterion was that individuals were
 187 able to follow the tasting instructions, including the predefined order, and complete the questionnaire.
 188 Among the 56 consumers, 2 were under 20 years old, 29 between 20 and 30, 8 between 30 and 40, 3
 189 between 40 and 50, and 4 between 50 and 59. Thirty-six were female (64%) and 20 were male (36%),
 190 39 were university students or doctoral/postdoctoral students, and 17 were school employees.

191 The instructions were to carry out the evaluation alone, on the same day as the products were
 192 distributed. All participants were acknowledged at the end of their evaluation with a chocolate bar.

193 **Table 2**
 194 Overview of the preparation of the six printable doughs.

	Rye (T170)		Soy		Wheat (T55)	
<i>Flour composition¹</i>						
Protein (%)	15.9		41.0		9.6	
Starch (%)	18.7		5.4		69.3	
Gluten (%)	NA		0		7.4	
Fiber (%)	23.8		19		2.5	
Sugar (%)	2.3		3.1		0.4	
<i>Product composition</i>						
Total water content (%)	60.0		59.0		65.0	
Apple puree (%)	0	20	0	20	0	20
Cinnamon (%)	2	2	2	2	2	2
<i>Recipe Name</i>	Rye	Rye + Apple	Soy	Soy + Apple	Wheat Wheat ²	Wheat + Apple
<i>Process</i>						
Mechanical treatment (min) at 120 rpm	12		12		12	
Thermo-mechanical treatment (min) at 100 rpm	22		27		15	

195 ¹The theoretical values (Ciqal database) are in bold, other values were obtained by the supplier or NA: Not
 196 available.

197 ² A duplicate of the wheat-based recipe has been produced and will be named “wheat*” in the results.

198 2.5.1.Sensory description

199 To determine the descriptors to be evaluated, a list of 15 descriptors pre-established by 6 panelists
 200 who had evaluated printed rye flour products flavored with cinnamon was used. This initial list of 15
 201 descriptors resulted from a 3-stage process inspired by the ISO 11035 method with the 6 judges:
 202 descriptor generation (total of 72), qualitative sorting (reduction to 47 descriptors) and then
 203 quantitative sorting (0-1 method). In our approach, the choice of descriptors was already obvious after
 204 the 0-1 sort, so we chose not to do the 0-5 sort. We added information about this methodology. This
 205 list of 15 descriptors was then discussed among the 4 panelists recruited and adapted to be relevant to
 206 the 7 products under study (Table 3). The panelists reached a consensus on the definition and the
 207 protocol evaluation of 14 descriptors for visual appearance, smell, texture (by touching and tasting)
 208 and taste (Table 4). During another session in sensory cabins, one evaluation of each product (2
 209 samples of each) in random order was carried out using an unstructured linear scale of 10 cm (ISO
 210 4121:2003) (Figure 1).

Descriptor: Sweet

Definition: Perception of sweetness via the tongue

Assessment Protocol: Take a bite and assess the intensity of the sweetness on the tongue.



211

212 **Figure 1.** Example of protocol and scale used to assess the descriptor “sweet”.

213

214 **Table 3**

215 Changes made to the list of descriptors after discussion among panelists.

	Descriptors retained	Descriptors removed	Descriptors added
Visual aspect	color, deformation, swelling, compact	none	space between printed lines
Texture (by touching)	hard	grainy, brittle	none
Odor	cereal, cinnamon	none	none
Texture (by tasting)	moisture	crispy, doughy	sticky, grainy
Taste/ flavor	cinnamon, sweet	burnt	cereal

216

217

Table 4

218

Definition and evaluation protocol of sensory descriptors in order of evaluation.

Type of descriptor	Descriptor	Definition of the scale	Evaluation protocol
* Use the first sample			
Visual	Color	Color intensity from beige to brown	Observe the entire surface of the product
	Deformation	Modification of the cylindrical shape from not to very deformed	Observe the cylindrical shape the product by the bottom surface
	Swelling	Modification of the heigh of the cylinder from not to very swollen	Observe the height of the product
	Space between print lines	Visibility of the space between the print lines from not to very visible	Observe the space between the print lines on the top surface
Handmade texture	Hard	From not to very hard	Compress the product between your fingers and assess the force needed to crush the product
* Use the second sample and divide product into two parts			
Visual	Compact	From not to very compact	Observe the proximity of components inside the product
Odor	Cereal	Cereal odor from not to very intense	Smell the inside of the product
	Cinnamon	Cinnamon odor from not to very intense	
Taste	Cereal	Cereal taste from not to very intense	Chew the product and then assess the intensity of the tastes
	Cinnamon	Cinnamon taste from not to very intense	
	Sweet	Sweet intensity from not to very sweet	
Texture during tasting	Moisture	from not to very moist	Chew the product then assess the amount of humidity in the mouth
	Sticky	from not to very sticky	Chew the product then assess the amount of product sticking to the teeth
	Grainy	from not to very grainy	Chew the product then rub the tongue on the palate to assess the graininess

219 2.5.2. Hedonic appreciation and CATA

220 For the consumer study, 56 consumers (70 % of students and 30 % of university employees, 36
221 women and 20 men) were recruited to evaluate the 7 products. Each consumer received one printed
222 and baked cylinder of each of the 7 products. The coded products were evaluated in the order of a
223 Latin square. Consumers were asked to give three scores based on their general appreciation of the
224 product, its visual appearance and its perception in the mouth. A 9-point hedonic scale was used,
225 where 1 represented a low appreciation and 9 a high appreciation.

226 After giving their hedonic appreciation of the product, consumers answered a CATA questionnaire.
227 Terms used in the CATA questionnaire were selected according to sensory descriptors used in the
228 sensory test and following a discussion between the authors and the panelists. The CATA question
229 included 10 terms related to sensory aspects (hard, soft, crispy, moisture, dry, sticky, brittle, grainy,
230 cereal and sweet). Consumers were asked to read the entire list of terms before beginning the
231 evaluation, and the terms were always presented in the same order to make it easier for them to
232 identify the terms to be checked off.

233 2.6. Statistical analysis

234 The experimental design and statistical analysis (PCA, CFA, desirability function) were performed
235 using JMP software (version 16.0, SAS Institute Inc., Cary, SC, USA). ANOVA and multiple
236 pairwise comparisons (Tukey (HSD)) were performed using XLSTATS (version 2024.3.0, Addinsoft,
237 Paris, France). Preference mapping was realized using MATLAB version: 9.13.0 (R2022b), Natick,
238 Massachusetts: The MathWorks Inc.

239 3. Results and discussion

240













241 3.1. Textural properties of printable dough

242 The firmness of formulated dough varies according to flour type and apple puree content (0 or 20%),
243 but for the same product the firmness is similar after preparation and after 1 night's storage, except for
244 wheat-based dough with and without puree which are less firm after 1 night's storage (Table 5).
245 Dough firmness is much higher for soy flour-based pasta (~ 35 N) than for rye (~ 20 N) and wheat
246 (~ 17 N) flour-based dough. Measurements after dough preparation have enabled us to compare
247 results with other projects and define an acceptable firmness range for printing (~ 10 to 40 N).
248 However, the firmness values are different from those in our previous article (Guénard-Lampron et
249 al., 2023), which could be explained by the addition of 2% cinnamon to the recipe. Measurements
250 after overnight storage are used to relate print quality to textural properties. Apple puree slightly
251 reduces firmness for all dough and this change is significant for rye and wheat doughs, while for soy
252 dough the decrease is not significant, which might be explained by the firm texture initially observed
253 in the soy dough (Table 5). These differences had no impact on the printability of the products, but we
254 did observe visual differences after baking the printed products. For example, rye-based products are

255 the darkest, which is not necessarily linked to its main composition (protein, starch, fibre, etc.) but
 256 rather to phenolic compounds, which are known to influence colour (Heiniö et al., 2008). Also, the
 257 difference in colour due to the addition of the apple puree is only visible in the soy flour-based
 258 product. This higher coloration observed for soy flour products when apple puree was added could be
 259 explained by a stronger Maillard's reaction enhanced by the reducing sugar contained in apple puree
 260 and the large quantity of available proteins in soy-based dough. For rye and wheat flour products, the
 261 addition of apple puree resulted in greater deformation of the 3D model during baking.

262 **Table 5**

263 Firmness (mean force) of printable dough after preparation and after 1 day.

Type of flour	Apple puree (%)	Firmness after preparation (N)	Firmness after 1 day (N)	Printed product	Baked product
Rye (T170)	0	19.8 ± 1.5 B	19.2 ± 1.6 B		
	20	14.8 ± 1.4 CD	15.0 ± 1.1 CD		
Soy	0	35.0 ± 2.6 A	36.8 ± 2.4 A		
	20	33.7 ± 0.7 A	34.8 ± 1.7 A		
Wheat (T55)	0	17.0 ± 0.6 BC	13.4 ± 1.2 D		
	20	13.0 ± 1.0 D	8.8 ± 1.5 E		

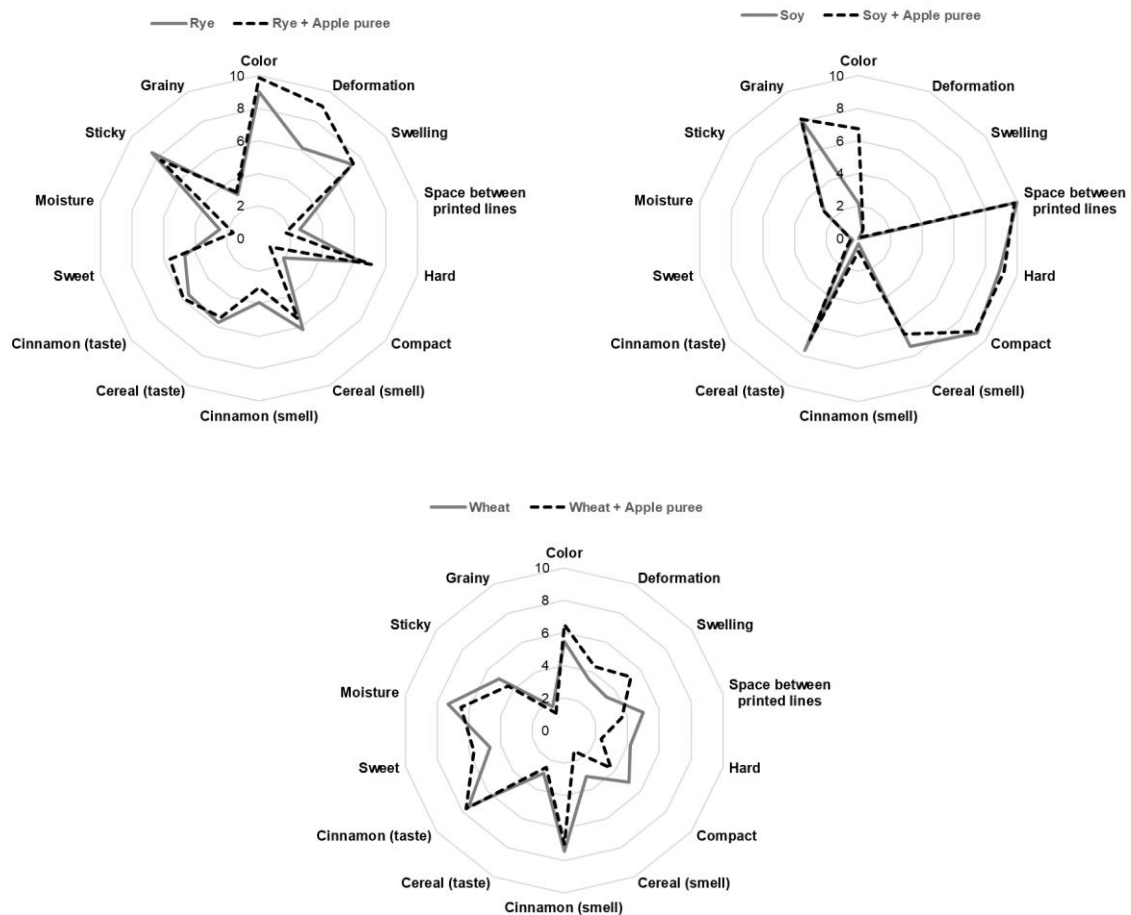
264 Different superscript letters indicate significant differences (Tukey's HSD test, $p < 0.05$)

265 3.2. Sensory map of printed products

266 **Figure 2** shows that products containing apple puree were slightly different with darker color (soy)
 267 and more distorted shape (rye). Soy flour products were more compact, grainier and harder (higher
 268 dough firmness), with a stronger cereal smell, cereal taste and very visible spaces between the print
 269 lines (good hold of the printing model). Rye and wheat flour products were sweeter, but cinnamon
 270 smell and taste were stronger for wheat flour products, followed by rye flour products, both well

271 pronounced compared to soy flour products. Wheat flour products were also more humid inside and
 272 moderately compact, while rye flour products were darker and stickier, more swollen, airy and
 273 deformed. Interestingly, as the only non-cereal flour among the three, soy flour gives a stronger cereal
 274 smell (7.4 for Soy and 6.5 for Soy + Apple) and taste (7.6 for Soy and 7.9 for Soy + Apple) to final
 275 products than rye flour does (for cereal smell: 6.2 for Rye and 5.5 for Rye + Apple and for cereal
 276 taste: 5.7 for Rye and 5.4 for Rye + Apple), while wheat-based products have the weakest cereal smell
 277 (~ 3.1 for Wheat and 1.4 for Wheat + Apple) and taste (~ 2.9 for Wheat and 2.5 for Wheat + Apple).
 278 This may be related to the high protein content in soy flour that enhances Maillard reactions and
 279 produces cereal-like flavors and tastes. Another explanation is the confusion between the descriptors
 280 “cereal” for grains and "nutty" for lipid-containing ingredients such as soy or nuts. For example, a
 281 whole-grain wheat bread could be associated with “nutty” attribute (Bhasin, 2020).

282



283

284 **Figure 2.** Sensory map of each product made from a) rye, b) soy or c) wheat flour according to the 14
 285 sensory descriptors. AP indicates products with apple puree. The wheat sensory map (without apple
 286 puree) represents an average of the product and its duplicate.

287 To quantify the observations based on the sensory map, an ANOVA analysis was carried out to study
 288 the impact of judge and product on the sensory descriptors (Table 6). The results shown in Table 6
 289 demonstrate that among the 14 descriptors, only "cereal (taste)" is not significant in distinguishing

290 different products, which means that the perceived intensity of cereal taste is not different for all 7
291 products. This suggests that the difference of the cereal taste isn't significant because of the strong
292 disagreement among judges, which could be related to the difficulty to distinguish "cereal" and other
293 similar attributes such as "nutty". Apart from the "cereal (taste)" descriptor, the products result in a
294 significant difference on the 13 other descriptors even if removing the effect of the judges who are not
295 necessarily always aligned on certain descriptors such as deformation, swelling, spaces between
296 printed lines, sweet and grainy. A multivariate analysis (not shown) also confirmed that the panelists
297 agreed with each other. In order to analyze more precisely the origin of the significant difference,
298 additional data with the estimated means and the classes of the multiple pairwise comparisons for
299 product (Tukey (HSD)) are available ([supplementary data](#)). These results enabled us to validate the
300 judges' assessment, since the duplicates of the wheat-based product without apple puree were always
301 in the same group. These classes also allow us to conclude whether the difference comes from the
302 flour or the presence of apple puree. For all descriptors except color and across all flours, there is no
303 significant effect between the product with and without apple puree. This allows us to conclude that
304 only the flour type, and not the addition of puree, influences these sensory descriptors. As for the
305 color aspect, the difference is only significant for soy-based products (class abc versus d). Meanwhile,
306 soy products don't share the same classes with neither rye nor wheat products for spaces between
307 printed lines, compact, cinnamon (taste), sweet and grainy aspects. At least one rye product shares
308 almost always the same classes with at least one wheat product apart from cinnamon (odor), which
309 demonstrates their similarity.

310 **Table 6**

311 ANOVA summary for all sensory descriptors

	Color	Deformation	Swelling	Spaces between printed lines	Hard	Compact	Cereal (odor)	Cinnamon (odor)	Cereal (taste)	Cinnamon (taste)	Sweet	Moisture	Sticky	Grainy
R ²	0.796	0.901	0.852	0.909	0.851	0.935	0.622	0.891	0.472	0.808	0.775	0.910	0.682	0.818
F	7.812	18.224	11.552	19.903	11.455	28.707	3.284	16.330	1.790	8.391	6.871	20.143	4.282	8.997
Pr > F	0.000	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.015	<0.0001	0.140	<0.0001	0.000	<0.0001	0.004	<0.000
Judge														<0.000
Pr > F	0.000	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.015	<0.0001	0.140	<0.0001	0.000	<0.0001	0.004	1
Product														<0.000
Pr > F	0.000	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.015	<0.0001	0.140	<0.0001	0.000	<0.0001	0.004	1

312

3.3. Relationship between sensory and nutritional properties of printed products

A Principal component analysis was carried out to establish the correlations between the sensorial descriptors of each product, the nutritional composition of each dough's formula, process-related information (water loss (%)) and textural characteristic (dough firmness (N)) of each dough (Figure 3). As the gluten content of rye flour was not available (measured or theoretical) and can vary widely (between 3.0 and 7.8 g/100 g when protein content varies between 5.5 to 11.2 g/100 g in 32 cultivars) (Xhaferaj et al., 2023), this data was not taken into account in the PCA. But we can point out that the gluten content of our products differs mainly for soya-based products, which are gluten-free. Components 1 and 2 of the PCA explain 95.2% of the total variance. Most of the variance was explained by component 1 (68.9%) and was related to all the sensorial descriptors studied and most of the nutritional and textural characteristics of the doughs. The content of starch, fiber, sugar and water and the percentage of water loss of the dough, with several sensorial descriptors (color, sticky, cereal smell, moisture e.g.) also contributed to the variance explained by component 2 (26.3%). The explanatory variables sugar and apple puree appear as relatively short vectors near the origin, indicating that their individual contributions to the variance explained by the first two principal components are limited. However, their orientation suggests a moderate association with sensory attributes such as sweetness, moisture and cinnamon smell and taste.

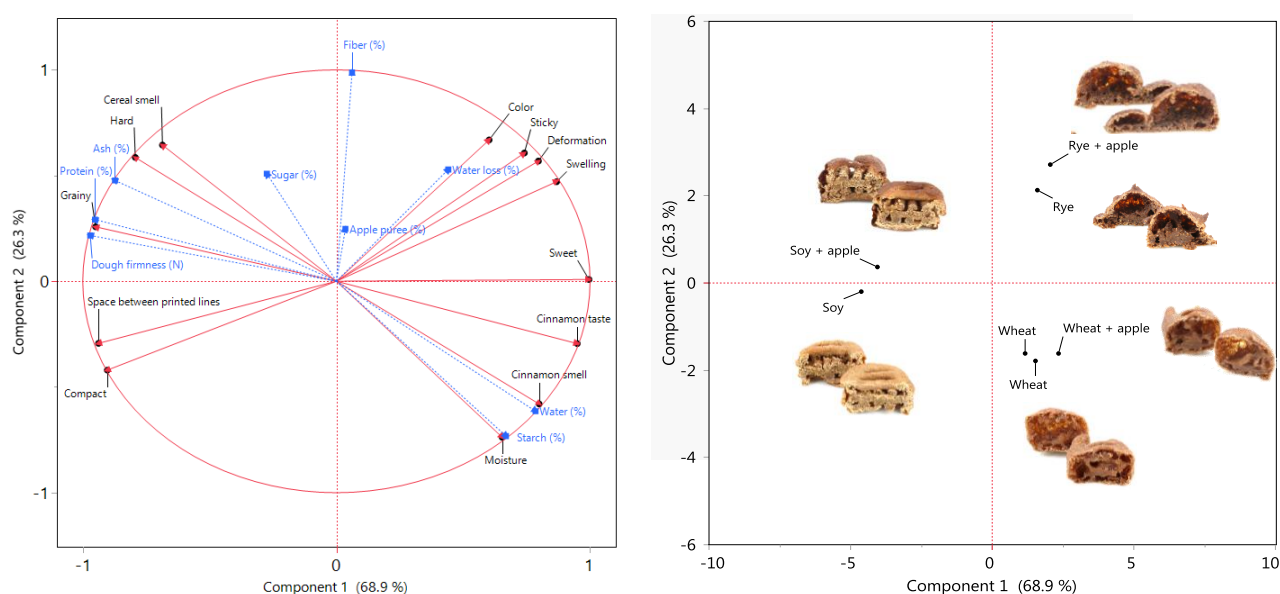


Figure 3. Principal component analysis (PCA map and correlation circle) of 3D-printed and baked products. Principal variables (red lines) were 13 significant sensorial descriptors; explanatory variables (blue dashed lines) were nutritional composition and technical characteristics of each dough. Doughs on the left of the plane are high in protein, ash and are firmer, related to a harder, grainier, more compact product with more obvious spaces between printed lines and stronger cereal smell. These are characteristics of soy-based products. These products are also drier, less colored, less sticky, less swollen with less deformation. In terms of smells and tastes, they are less sweet and have milder cinnamon taste and smell. In the other hand, this observation also suggests the correlation between the mean force during back extrusion of the dough and the hard and compact aspects of the

340 final products, giving the possibility to predict sensorial description based on textural properties of the
341 doughs. In addition, the link between a perception of a hard final product and a firm dough texture can
342 be traced back to the nutritional composition, which implies a higher content of ash and protein and
343 lower water content, as well as that of starch. Since starch has the role of retaining water in the dough
344 process, this explains the correlation between a higher starch content giving a less firm dough and a
345 moist final product, and conversely, by using a more protein-rich recipe therefore containing less
346 starch, the finished product is harder.

347 Meanwhile, doughs on the right part, where rye and wheat-based products can be found, are richer in
348 starch and water. Rye doughs in the upper right part are correlated to a more colored, sticky,
349 deformed, swollen and sweeter product while wheat doughs have stronger characteristics on higher
350 moisture and sweetness with pronounced cinnamon taste and smell. Actually, rye products are also
351 known as colored compared to other cereal-based products like oat and millet and have sweeter taste
352 than these two cereals and sorghum-based products (Torbica et al., 2019).

353 Another observation is that the loss of water during the drying of the product is not correlated to the
354 moisture sensation in the final product. It is however correlated to a more sticky and less compact
355 product, which can be explained by a loss of water greater in products that are initially very humid,
356 and this loss of water does not completely counterbalance the humidity initially present in the dough.
357 The finished products therefore remain more sticky and less compact compared to others.

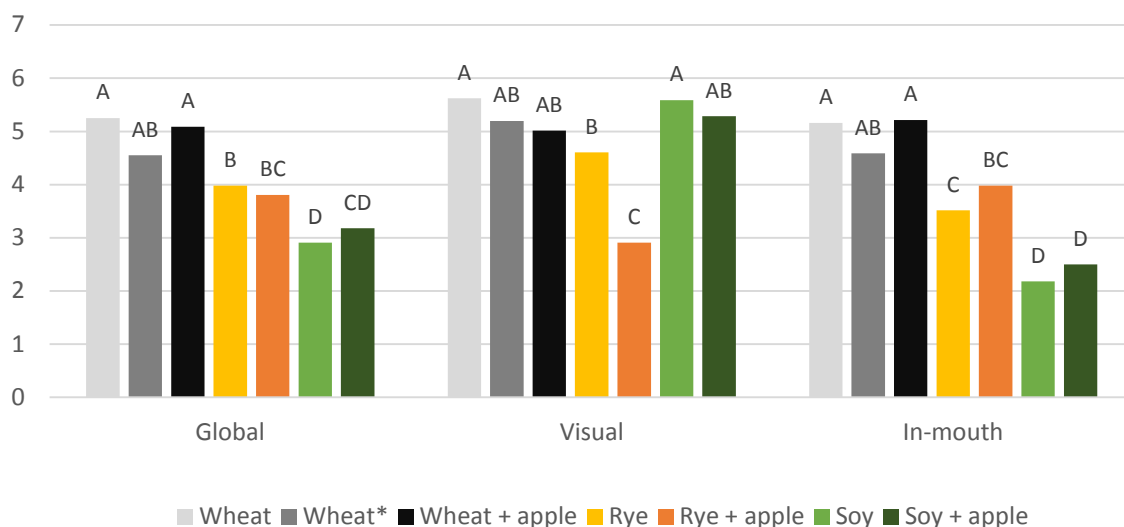
358

359 3.4. Consumer perception of printed products

360 The hedonic scores evaluated by the 56 consumers shown in [Figure 4](#) show consumer preference for
361 the 7 printed products. The highest scores remained around 5.5, indicating moderate acceptance.
362 There are 3 possible explanations: 1) the awareness that the products were 3D-printed, potentially
363 influencing perception, 2) simple 3D shapes were proposed, with room for more appealing designs in
364 future projects, 3) flavoring choices that may not have suited all consumers, warranting further
365 exploration. These could be partially confirmed by comments of consumers: 8 participants mentioned
366 a strange texture as some found the soy-based products too dry and compact, while rye-based ones
367 were considered too soft and incomparable with classic snacks like biscuits. At least 2 participants
368 disliked the cinnamon flavor, and 8 participants noted insufficient sweetness.

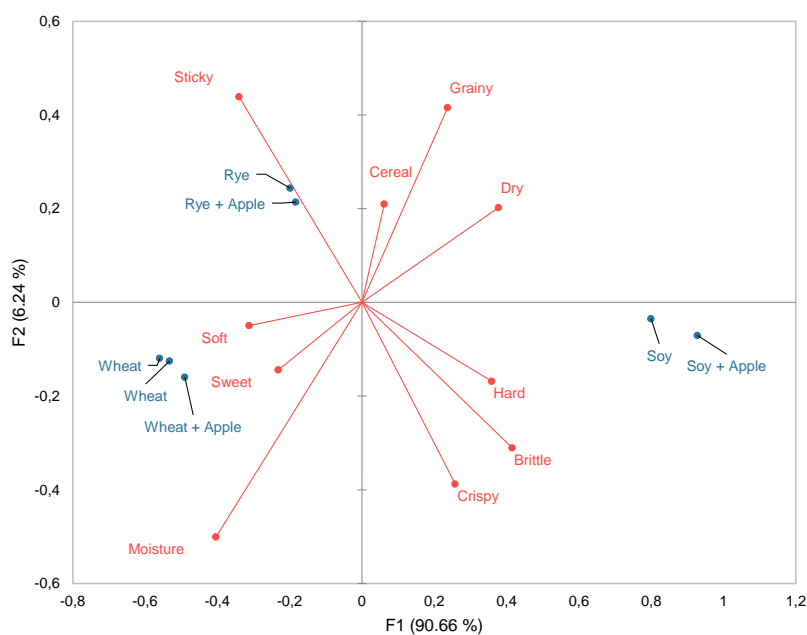
369 For overall ratings, wheat-based products are the most popular while soy-based products are the least
370 popular. Looking in more detail, soy-based products are nevertheless appreciated at the visual level, it
371 is the texture in-mouth aspect which is not appreciated by consumers with an average score of 2.5
372 (class D) and 2.2 (class D) for products with and without apple puree. For wheat and soy products, the
373 difference in appreciation with and without apple puree is not highlighted. For rye-based products,
374 only the visual score makes the difference between products with or without apple puree: 4.6 (class B)
375 versus 2.9 (class C), probably due to the important deformation of the product with apple puree. The
376 low global and in-mouth appreciation of soy products is probably related to their hard, compact and

377 dry mouthfeel, as well as beany flavor (not included in this study) and taste which are characteristic of
 378 raw soybean flour, which can be improved by pretreatment like steaming or roasting (Shin et al.,
 379 2013).



380
 381 **Figure 4.** Global, visual and in-mouth appreciation of the 7 products with classes of multiple pairwise
 382 comparisons for product (Tuckey (HSD)). Different letters of significance indicate that products are
 383 significantly different within one of the three ratings (overall, visual or in-mouth).

384 In order to understand the correlation between consumers' appreciation of taste, texture and overall
 385 appearance and their perception of the various descriptors of the printed products, a CATA test was
 386 also carried out and the results were analyzed using the CFA method. This test shows whether
 387 consumers describe products in the same way as the sensory description by panelists, so that we can
 388 confirm whether their hedonic appreciation is based on the same basis as previous descriptions
 389 concluded by PCA method.

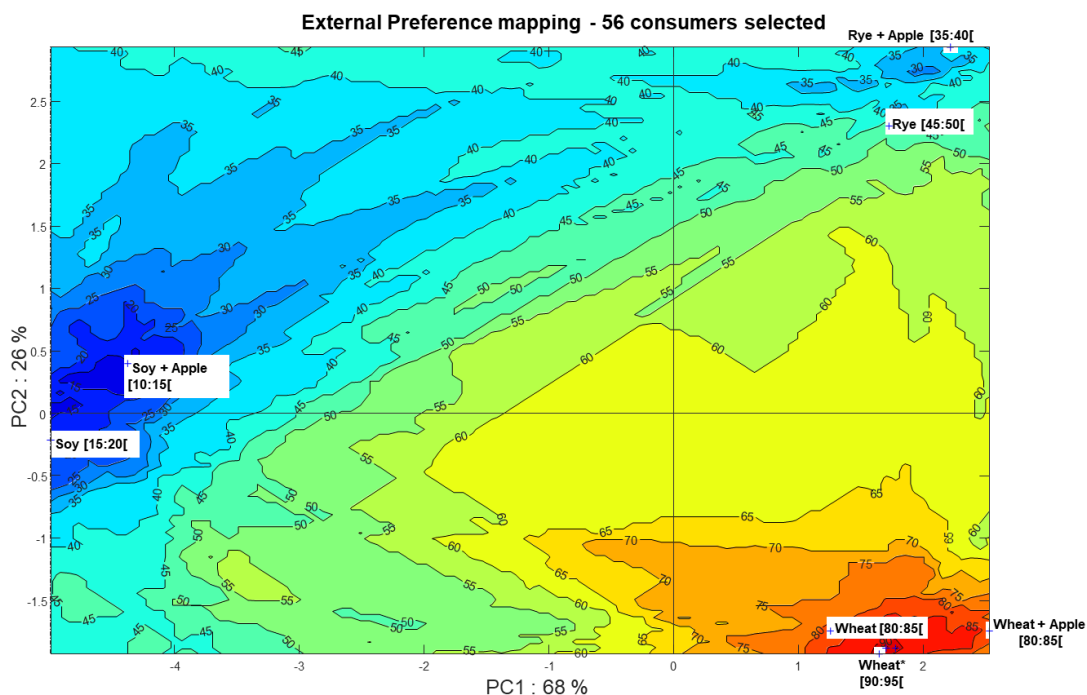


390
 391 **Figure 5.** CFA of 3D-printed and baked products obtained from the CATA evaluation.

392 According to the CFA results (Figure 5), wheat products are related to moist, sweet, soft, not crispy,
 393 not brittle, not dry and not grainy characteristics. Rye products are related to sticky and soy products
 394 are in the opposite position of products based on wheat. These results show that CATA results are
 395 close to the sensory description by panelists despite lack of intensity, which is not surprising as CATA
 396 was demonstrated nearly as efficient as descriptive analysis of flash profile in other sensory studies
 397 (Hunaefi & Marusiva, 2021; Kim et al., 2023). Compared to the principal component analysis, the
 398 characteristics are less represented in the CFA, the coordinates of the vectors are less close to 1. Even
 399 if the descriptors are not the same, it is still possible to find the correlation between the moisture,
 400 sweet and soft aspects (the opposite of hard in the PCA), and these characteristics are anticorrelated to
 401 grainy and dry aspects. The sticky descriptor correlates with neither soft nor moist and is highly
 402 related to rye-based products. Two new descriptors, crispy and brittle, have been introduced and are
 403 mainly linked to soy-based products.

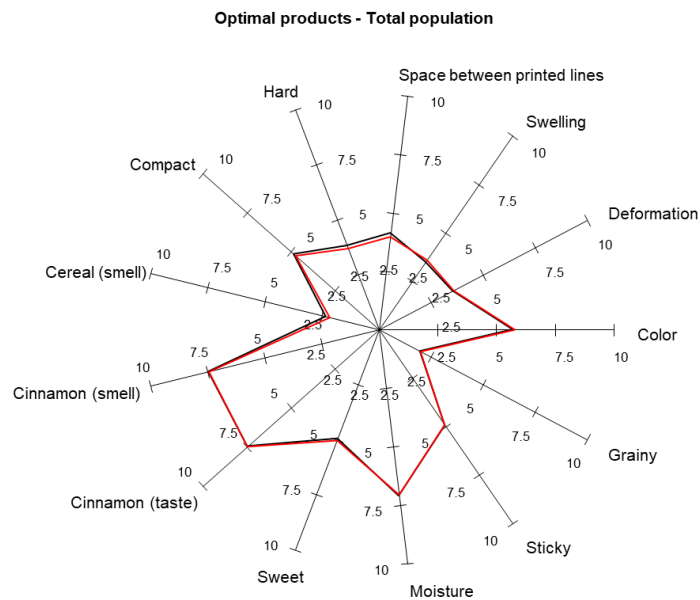
3.5. Relationship between sensory properties and consumer preferences

404 An external preference mapping using the principal component analysis on the sensory data and the
 405 global appreciation of the consumers was performed (Masson et al., 2016). Figure 6 shows the
 406 preference mapping where wheat flour products are consumers favorite (80-95%), followed by rye
 407 (35-50%) and soy (10-20%). In contrast to the averages presented in Figure 3, where only the visual
 408 aspect makes the difference in product appreciation with and without puree, and only for rye-based
 409 products, the difference in appreciation between products with and without apple puree are more
 410 visible in the preference mapping. It is possible to observe that products with apple puree are less
 411 appreciated than products without.
 412



413 **Figure 6.** Preference mapping based on the global appreciation of products by consumers (n = 56) and
 414 sensory description of the 7 printed products.
 415

416 From this mapping, we were able to extract in the red zone of the map the ideal values to target for
 417 each of the sensory descriptors (Figure 7). This gives us a slightly distorted and domed product and
 418 the spacing between the lines doesn't have to be very visible. The product should be moderately
 419 colored with a moderately sticky texture, moderately compact, not hard or grainy but rather moist.
 420 terms of smell and taste, it's ideal to have very little cereal smell, a moderate sweetness and a
 421 relatively strong cinnamon smell and taste. As for apple puree, the ideal product would contain none.
 422 However, in this study, the optimal product was not tested since our aim was rather to obtain sensory
 423 and hedonic information as well as links between this information in order to develop a knowledge
 424 base on the use of these flours in food 3D printing. These results show that it would be interesting to
 425 make a flour blend to obtain moderate values in certain aspects. For example, by comparing with the
 426 sensory maps of the products (Figure 1), we can hypothesize that a blend based on wheat and soy
 427 flour would result in a less firm and slightly moister product than one based solely on soy flour.
 428 Similarly, a mixture based on wheat and rye flour could improve the color and reduce the deformation
 429 of printed products.



430

431 **Figure 7.** Ideal sensory properties to target according to preference mapping.

432 4. Conclusions

433 This study integrated nutritional composition, textural properties related to printability and sensory
434 descriptions and appreciation of 3D printed products based on wheat, rye and soy flour. Textural
435 analysis revealed that soy flour resulted in the highest dough firmness, while apple puree slightly
436 reduced firmness across all the formulations. Although this did not affect printability, it influenced the
437 appearance of final baked products, especially for rye-based ones. These findings align with sensory
438 evaluation performed by panelists (descriptive analysis) and consumers (CATA).

439 Descriptive analysis highlighted that flour type had a stronger impact on sensory properties than apple
440 puree. Principal Component Analysis (PCA) confirmed strong correlations between sensory
441 descriptors, nutritional composition, and dough textural properties. Soy-based products were
442 perceived as firmer, drier, grainier, and had stronger cereal aromas, while rye- and wheat-based
443 products were described as sweeter, moister, and more deformable. Consumer preference analysis
444 (PREMAP) showed a strong preference for wheat-based products (80-95%), followed by rye (35-
445 50%) and soy (10-20%) among 56 consumers. The dry, firm and grainy texture of soy products could
446 play a key role in this evaluation, as wheat and rye-based products were perceived as more appealing.
447 Apple puree had little impact in overall appreciation, except for rye-based products, where it
448 negatively impacted visual appeal.

449 These findings suggest opportunities to improve consumer acceptance of these 3D-printed products
450 by optimizing product shape and enhancing flavor profiles. The observed correlation between the
451 firmness of the dough and the sensory texture descriptors (compactness and hardness) indicates the
452 potential to predict sensorial perception based on textural properties.

453 To further refine the formulation of 3D-printed foods that are both nutritionally relevant and
454 sensorially appealing, several complementary research directions should be pursued. First, a more in-
455 depth nutritional characterization of the products is necessary, with particular attention to minor
456 bioactive compounds such as polyphenols, which may not only enhance the nutritional profile but also
457 influence sensory properties (flavor). Second, the characterization of color changes after cooking
458 should be expanded using instrumental colorimetry to better understand how flour composition and
459 added ingredients impact Maillard reactions and pigment degradation, both of which play a role in
460 visual appeal and perceived baking. Third, instrumental analysis of structural parameters, such as
461 particle size distribution, should be deepened to assess its influence on dough rheology, printability,
462 and final texture. Since granularity and viscosity directly affect the quality and stability of the printed
463 structure, linking these parameters to consumer-perceived textural attributes will be critical. These
464 investigations will allow for a more integrated understanding of how ingredient choice and processing
465 parameters influence both the technical performance and sensory quality of 3D-printed foods.

466 Finally, while consumers showed a greater interest in wheat-based printed products, the other two
467 flours, especially rye flour, presents sensory potential when incorporated into wheat-based
468 formulations at partial substitution levels, which is also a common practice in food design. The
469 sensory insights from this study provide a valuable foundation for a reasoned approach to flour blend
470 formulation, enabling the optimization of both nutritional value and consumer enjoyment of 3D-
471 printed products.

472 **Declaration of interests**

473 The authors declare that they have no known competing financial interests or personal relationships
474 that could have appeared to influence the work reported in this paper.

475

476 **Data availability**

477 Data will be made available on request.

478

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634 Additional data

635 Table 1. ANOVA summary with estimated averages by product name and pairwise multiple comparisons for Product Name (Tukey (HSD))

636

Modality	Color	Deformation	Swelling	Spaces between printed lines	Hard	Compact	Cereal (odor)	Cinnamon (odor)	Cereal (taste)	Cinnamon (taste)	Sweet	Moisture	Sticky	Grainy
Rye + Apple	9,885 a	9,014 a	7,395 a	1,659 c	7,101 ab	0,854 d	5,462 abc	3,014 bc	5,364 a	5,910 a	5,625 a	1,628 b	7,692 a	3,151 b
Rye	9,021 ab	6,160 ab	7,323 a	2,564 c	6,440 abc	1,927 cd	6,213 abc	3,934 b	5,747 a	5,532 a	4,687 a	2,462 b	8,429 a	2,988 b
Wheat + Apple	6,530 abc	4,351 b	5,259 ab	3,643 bc	2,340 d	3,664 bc	1,391 c	6,979 a	2,514 a	7,689 a	5,696 a	6,498 a	4,392 ab	1,172 b
Wheat	5,280 cd	3,585 bc	3,467 bc	6,125 b	4,369 bcd	5,233 b	4,145 abc	7,285 a	2,984 a	7,628 a	4,435 a	7,446 a	5,216 ab	0,971 b
Wheat*	5,653 bcd	3,403 bcd	3,208 bc	3,824 bc	3,951 cd	4,957 b	2,128 bc	7,590 a	2,811 a	7,411 a	4,930 a	7,155 a	5,005 ab	2,312 b
Soy + Apple	6,728 abc	0,669 cd	0,146 c	9,808 a	9,142 a	9,170 a	6,522 ab	0,776 c	6,872 a	0,939 b	0,508 b	0,630 b	2,809 b	8,141 a
Soy	2,126 d	0,520 d	0,000 c	9,971 a	8,874 a	9,301 a	7,365 a	0,335 c	7,624 a	0,757 b	0,345 b	0,630 b	2,675 b	8,151 a
Product Pr > F (Modèle)	0,000	<0,0001	<0,0001	<0,0001	<0,0001	<0,0001	0,015	<0,0001	0,140	<0,0001	0,000	<0,0001	0,004	<0,0001

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