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Effect of “*shape*” on technological properties and nutritional quality of chickpea-corn-rice gluten free pasta

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ABSTRACT

Macroscopic and microscopic food structural characteristics play an important role in product’s technological properties and nutritional attributes. The effects of macroscopic (pasta shape, PS) and microscopic (flour particles, FP) structural attributes were independently investigated in gluten-free (GF) chickpea-corn-rice short pasta (50% chickpea) considering cooking quality, physicochemical attributes, thermal properties, *in vitro* digestibility of starch (IVSD) and protein (IVPD). Different PS (rigatoni, fusilli, fusilli piccolo, caserecce, gnocchetti sardi) and different chickpea FP (conventional, precooked, fine, coarse) were considered. With regards to PS effect, rigatoni-shaped pasta differed significantly from other PS having the longest cooking time, a harder and less adhesive texture, the highest gelatinization enthalpy, the lowest IVPD, and higher resistant starch content. The chickpea FP modulated the flour pasting properties and slightly impacted both pasta cooking quality and nutritional characteristics regarding IVSD and IVPD. This work suggested that pasta structural attributes, especially PS, can modify pasta cooking quality, physicochemical, and nutritional characteristics and should, therefore, be considered in rational product design to provide food products with desired properties.

1. Introduction

Gluten-free (GF) pasta is traditionally formulated with corn and rice (i.e., flour and/or starch) and it is characterized by low nutritional quality, mainly due to the high content of rapidly digestible starch (RDS), and poor technological properties (Calvo-Lerma et al., 2019; Marti & Pagani, 2013; Morreale et al., 2019; Pellegrini & Agostoni, 2015; Trevisan, Pasini, & Simonato, 2019). In recent years, GF pasta has undergone extensive innovation following the agri-food market trends calling for healthy, sustainable, and protein-rich products alternative to the traditional ones (Foschia, Horstmann, Arendt, & Zannini, 2017; Lorenzo, Sosa, & Califano, 2018; Tomar, Pathak, & Pradhan, 2022, pp. 73–96).

Therefore, considerable interest has risen in legumes as functional ingredients to improve GF pasta’s properties. Among them, chickpea is of high interest due to their relatively high protein content, good technological functionality and limited impact on product sensory characteristics (Day, 2013; Sanjeewa, Wanasundara, Pietrasik, & Shand, 2010). Some attention has been given to chickpeas in GF pasta formulation with evidence of positive effects on product’s nutritional profile (significant amount of protein and fiber contents) and glycemic-related health benefits (Garcia-Valle, Bello-Pérez, Agama-Acevedo, & Alvarez-Ramirez, 2021; Romano, Ferranti, Gallo, & Masi, 2021; Suo et al., 2022; Turco, Bacchetti, Morresi, Padalino, & Ferretti, 2019).

Awareness of the importance of food structure in modifying product technological quality, characteristics and constituents’ bioavailability has risen as one object of particular interest in recent years (Aguilera, 2019; Aguilera, 2022; Azeredo, Tonon, & McClements, 2021; Capuano & Janssen, 2021; Palchen et al., 2022). Food structure could be generally rolled out in terms of pasta shape (PS; macroscopic level) or the size of flour particles (FP; microscopic level). The PS has been reported to affect cooking quality, texture, microstructure, *in vitro* starch and protein digestibility (Shreenithee & Prabhasankar, 2013). Noteworthy, pasta shape was reported to affect the percent of slowly digestible starch

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(SDS; Dodi et al, 2023), the glycemic response in semolina pasta (Pugnaloni et al., 2022), and the eating behavior and structural breakdown during mastication which may directly affect the post-prandial glycemic response (Suo, Mosca, Pellegrini, & Vittadini, 2021; Vanhatalo et al., 2022). However, the available effort to understand the effect of shape on pasta properties has been very limited when it comes to GF pasta and even none in the case of legume-containing GF food products. In addition, the size of flour particles (FP) can be easily controlled through the milling process to preserve cell integrity (coarse flour) or to cause cell wall breakage and leakage of cell components (fine flour). Cell walls may act as a physical barrier to digestive enzymes thus retarding/reducing nutrients availability (Capuano & Pellegrini, 2019; Dhital, Bhattarai, Gorham, & Gidley, 2016; Duijsens et al., 2023; Korompokis, De Brier, & Delcour, 2019; Pellegrini, Vittadini, & Fogliano, 2020; Rovalino-Córdova, Fogliano, & Capuano, 2018; Rovalino-Córdova, Montesdeoca, & Capuano, 2021). Solubility of dietary fiber, physical and cooking quality of semolina pasta can also be affected by the size of FP (Dalbon, Grivon, & Pagani, 1996; Donnelly & Ponte, 2000; Sacchetti, Cocco, Cocco, Neri, & Mastrocola, 2011). However, little information is currently available on the case of GF pasta except for one case of pearl millet based pasta (Jalgaonkar & Jha, 2016). On the other hand, GF pasta production requires extensive starch gelatinization as amorphous starch acts as a structuring element within the product (Marti, Pagani, & Seetharaman, 2011; Marti, Caramanico, Bottega, & Pagani, 2013), and this might be facilitated by using pregelatinized corn and rice flours as ingredients. However, the drawback of extensive starch gelatinization is its high accessibility to digestive enzymes and increased glycemic index (Dona, Pages, Gilbert, & Kuchel, 2010; Ross, Brand, Thorburn, & Truswell, 1987). To the authors' best knowledge, no study has investigated chickpea FP effect, and the use of thermal-treated chickpea flours in GF pasta products.

Based on these considerations, it was hypothesized that pasta pieces with different PS and flours with varying FP can alter pasta cooking and technological quality, *in vitro* starch and protein digestions. The aim of the present work was, therefore, to verify independently the effect of PS and FP (i.e., particle size and flour precooking), on product quality (technological properties) as well as *in vitro* starch and protein digestibility of chickpea-corn-rice GF pasta.

2. Material and methods

2.1. Flours, particle size and pasting properties

Commercial precooked white corn (corn), precooked brown rice (rice) and chickpea flours were obtained from Martino Rossi SpA (Cremona, Italy). For chickpea flour, a flour that underwent standard milling (conventional), a micronized flour (fine), a large granulometry flour (coarse) and a precooked flour (precooked) were included. The chemical composition of all flours was taken from product technical sheets (Table 1).

Flour particle size distribution was determined by fractionating flours using a sieve shaker (RETSCH, Germany) with two mashes (125 and 425 μm). Flours (20 g) were shaken for 5 min and then the three collected fractions (<124 μm, 125–425 μm and >426 μm) were weighed. Flour size distribution was then calculated (% weight; Table 1).

The pasting properties of all flours and their blend used for pasta making (50% w/w corn: rice [3:2] and 50% w/w chickpea flour) were investigated by a micro visco-amylograph (Brabender, GmbH, Germany) as previously reported (Moreno-Araiza, Boukid, Suo, Wang, & Vittadini, 2023) with slight modifications. Each flour and flour blend was mixed with deionized water to form a 15% homogeneous suspension (dry weight basis, w/w). Each suspension (115 g) was loaded into the visco-amylograph and then heated, while stirring, from 30 °C to 93 °C at a heating rate of 7.5 K/min, held at 93 °C for 5 min, cooled to 30 °C at 7.5 K/min, and held at 30 °C for 1 min. Onset gelatinization temperature (°C), peak viscosity (BU), breakdown (BU), final viscosity (BU), and setback viscosity (BU) were obtained.

2.2. Pasta formulations and manufacturing

Pasta was produced in the pilot plant of Massimo Zero company (Merano, Italy) as previously reported (Suo et al., 2022). All pasta formulations were designed to contain 50% w/w of a mix of corn and rice flours (corn:rice = 3:2 w/w) and 50% w/w of chickpea flour. During pasta processing, all formulations needed about 10 kg of water for 30 kg flour except for the coarse flour which needed 12 kg of water for 30 kg flour. Briefly, blends of corn and rice flours were mixed for 8 min, and chickpea flour was added, followed by a further mixing for 5 min. The

Table 1
Nutritional composition, particle size distribution, and pasting properties of flours used for gluten free pasta production.

	CORN	RICE	CHICKPEA			
	Precooked	Precooked	Conventional	Fine	Coarse	Precooked
Composition						
Energy (kcal/100 g)	350	358	353	354	353	355
Total fats (g/100 g)	<0.1	3.3	5.4	5.9	5.4	5.8
of which saturates (g/100 g)	<0.1	0.8	0.8	0.9	0.8	0.1
Total carbohydrates (g/100 g)	80.4	72.2	48.5	45.9	48.5	47.3
of which sugars (g/100 g)	0.8	0.7	4.0	2.5	4.0	5.1
Protein (g/100 g)	6.3	7.7	23.6	22.6	23.6	23.1
Fiber (g/100 g)	1.8	4.4	8.4	13.3	8.4	10.5
Salt (g/100 g)	0.02	0.04	0.10	0.10	0.10	0.02
Moisture content (g/100 g)	10.3	9.6	9.4	9.9	9.7	9.0
Particle size distribution (%) ($)						
>426 μm	0	1 ± 0	1 ± 1	0	36 ± 3	0
125–425 μm	82 ± 3	78 ± 2	80 ± 5	13 ± 4	62 ± 2	83 ± 3
<124 μm	18 ± 1	21 ± 1	19 ± 4	87 ± 6	1 ± 1	17 ± 6
Pasting properties (*)						
Onset gelatinization temperature (°C)	70.6 ± 0.4E	78.1 ± 0.2CD	84.0 ± 0.7B	78.4 ± 0.4CD	89.0 ± 0.8A	77.8 ± 0.4D
Peak viscosity (BU)	163.7 ± 4.4B	88.0 ± 3.6D	103.0 ± 6.7C	180.7 ± 1.2A	31.7 ± 1.5E	103.0 ± 3.5C
Peak time (min)	8.9 ± 0.6D	9.9 ± 0.2CD	12.6 ± 0.2AB	11.7 ± 0.8B	13.1 ± 0.3A	10.4 ± 0.0C
Final viscosity (BU)	403.7 ± 14.3A	232.0 ± 8.5B	113.3 ± 6.0E	185.7 ± 3.5C	64.7 ± 2.3F	148.3 ± 4.6D
Breakdown (BU)	5.7 ± 0.6A	3.3 ± 0.6AB	1.3 ± 0.6BCE	2.0 ± 1.7BCE	0.0 ± 0.0C	3.0 ± 0.0B
Setback (BU)	226.3 ± 2.0A	139.0 ± 3.5B	14.7 ± 5.6F	12.3 ± 1.5F	31.0 ± 9.6E	45.7 ± 1.5D

($) Data are means of triplicates ± standard deviation.
(*) Data are means of triplicates ± standard deviation. Means followed by different letters in each line are significantly different at $p < 0.05$.

dough mixture was then kneaded for 5 min in the mixer basin under vacuum (−0.8 bar). Then it was extruded at 50 Hz using a standard pasta press screw extruder at a controlled barrel temperature (25 ± 1 °C) with pressure of 80 bar. Extruded pasta pieces were placed on a single layer in drying trays and were dried for 8 h at max 55 °C in a dryer (La Parmigiana, Fidenza, Italy). Dry pasta was cooled to room temperature, packed in sealed polyethylene bags, and kept at room temperature for further analysis.

To verify the effect of different PS on parameters of interest, GF pastas were produced using the standard milled chickpea flour (i.e., conventional) but extruded in five different shapes (i.e., fusilli, fusilli piccolo, caserecce, gnocchi sardi, and rigatoni; Fig. 1A). Pastas were also produced with the same shape (rigatoni) but with the four different chickpea flour types (i.e., fine, coarse, precooked, and conventional; Fig. 1B) to verify the effect of FP. The obtained GF pasta samples were named directly as “fine”, “coarse”, “precooked” and “conventional”. It is worth pointing out that “rigatoni” and “conventional” in the “effect of PS” and “effect of FP” sections, respectively, are the same sample, which has been investigated and presented in a previous study (Suo et al., 2022).

2.3. Pasta technological quality characterization

Pasta cooking was done by placing 30 g of dry pasta in 300 ml boiling deionized water and holding it for the predetermined optimal cooking time (OCT). Cooked pasta and cooking water were immediately separated with a drainer for the following analysis. Three cooking batches for each pasta type were analyzed and results were reported as the average of three replicates.

Pasta optimal cooking time (OCT; min) was the consensus time determined by eight technicians working in the GF pasta producer that tasted pasta samples cooked for increasing times and evaluated products’ hardness and adhesiveness.

Pasta cooking loss during cooking was evaluated according to AACC official method 66–50.01 (AACC International). Cooked pasta and cooking pot was rinsed with water (approximately 50 mL), and the rinsed water was combined with cooking water for drying. Cooking/rinse water was dried in an oven to constant weight, and cooking loss was expressed as percentage solids (%) to raw pasta.

Length and thickness of raw and cooked pasta were determined using a calliper (Suo et al., 2022). Percentage length and thickness gains (%) upon cooking were calculated with respect to uncooked pasta pieces dimensions. At least ten pasta pieces from each cooking batch were measured.

Moisture content, color, and texture of cooked pasta were measured as previously reported (Suo et al., 2022). Briefly, moisture content was measured by drying cooked pasta at 105 °C to constant weight and reported as percentage moisture (%) with respect to original cooked pasta weight. Pasta color was determined using a colorimeter (Minolta, Chroma Meter CR-400, Japan) with illuminant D65 and 2° angle of observer including L* (lightness, 0: black; 100: white), a* (−: greenness; +: redness) and b* (−: blueness; +: yellowness). Pasta texture was measured using a Food Texture Analyzer (TA1 Texture Analyzer, AMETEK, USA) equipped with a 100N load cell. Hardness, measured as the maximum force at break from a cutting test (at 2 mm/s) using a flat blade, was expressed as standardized hardness “N/mm^2” in the effect of PS (to correct for different pasta shapes) and “N” in the effect of FP. Adhesiveness (J) was evaluated by a compression test using the cylinder probe (25mm × 100 mm) with a compression force at 30N (10s of holding time) at 1 mm/s and was recorded as the work to separate the sample from the probe. Ten readings were collected for each parameter in each cooking batch.

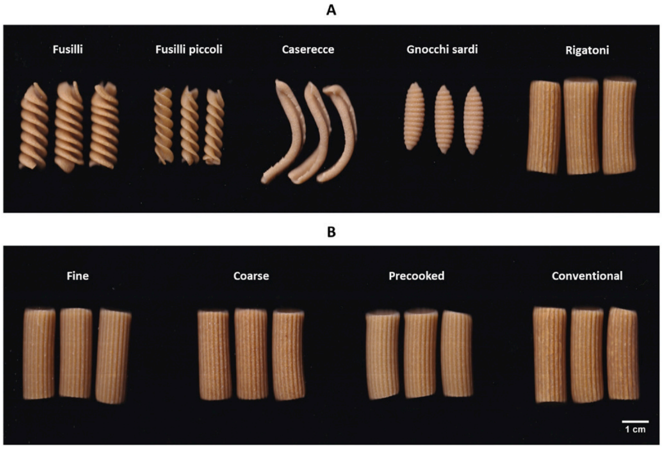

Fig. 1. Shape of raw pasta (produced with 50% w/w corn: rice [3:2] and 50% w/w chickpea flour; A-pasta with different shape, B- pasta made with different chickpea flour) considered in this study.

Thermal properties were evaluated on freeze-dried cooked to OCT pasta samples. After cooking, samples were cooled by soaking in cold water, cut into 1 mm pieces, freeze-dried, and ground. A differential scanning calorimetry (DSC8000, PerkinElmer Inc., Waltham, MA, USA) was used. Samples were weighed into steel pans, distilled water was added (1:3 w/w sample:water), then the pans were sealed and left at room temperature. After 20 h, samples were heated from 25 to 170 °C at 10 K/min. The onset temperature, the peak temperature, the offset temperature, and the gelatinization enthalpy were recorded. Experiment was carried out in triplicate on each cooking batch.

2.4. Pasta nutritional quality characterization

The *in vitro* starch digestion (IVSD) was carried out following the method detailed by previous study (Englyst, Englyst, Hudson, Cole, & Cummings, 1999) on cooked pasta samples. The *in vitro* glucose released was measured colorimetrically (GODPOD 4058, Giesse Diagnostic S.r.l., Rome, Italy). The value for rapidly digestible starch (RDS) and slowly digestible starch (SDS) corresponds to the glucose released after 20 min, and between 20 min and 120 min of enzyme hydrolysis, respectively. The amount of the available starch (AS) was calculated as the sum of RDS and SDS. In addition, the slowly digestible starch/available starch (SDS/AS) ratio was calculated on cooked pasta based on the SDS and AS contents. For each treatment, batches were analyzed in triplicate. The resistant starch (RS) was measured on cooked samples using an enzymatic assay kit (Megazyme Ltd., Ireland), which is based on AOAC Method 2002.02, AACC Method 32–40.01 (AACC International) and CODEX Type II Method, while total starch (TS) in pasta samples was analyzed following the assay based on AOAC Method 996.11, AACC Method 76–13.01 (Megazyme Ltd., Ireland). RS/TS (%) was therefore calculated based on TS and RS contents analyzed in the cooked samples. Starch fractions were all expressed as g/100g on dry matter (DM).

The *in vitro* protein digestibility (IVPD) of cooked pasta samples was evaluated as detailed by (Kamble et al., 2019). Briefly, samples were hydrolyzed in a 0.1 M HCl solution containing pepsin (P7000, Merck KGaA, Darmstadt, Germany) at 37 °C for 3 h. Then, 0.2 M of a NaOH solution was added, followed by a pancreatin (P7545, Merck KGaA, Darmstadt, Germany) solution (0.2 M phosphate buffer, pH = 8). Samples were further incubated for 24 h at 37 °C. At the end of the enzyme hydrolysis, a 10% v/v TCA solution was added to the suspension. The protein content was estimated after centrifugation in the collected supernatants. The IVPD was calculated as a percentage considering the nitrogen content of samples before the enzyme hydrolysis after correction for blank. The content of protein in pasta samples was quantified using Kjeldahl method (AOAC, 2000).

2.5. Statistical analysis

All data were subjected to one-way analysis of variance (ANOVA) using IBM SPSS Statistics 22 (IBM Corporation, New York, USA) to identify the significant difference ($p < 0.05$) among samples by Duncan's test. Principal component analysis (PCA), based on average values of cooking and technological quality, was carried out by projecting into the first two principal components (PC1 and PC2) by using XLSTAT (Addinsoft, New York, USA).

3. Results and discussion

3.1. Flour characteristics

Macronutrients' composition and dimensional attributes of flours are presented in Table 1. As expected, corn and rice precooked flours had greater carbohydrate and lower protein and fiber contents than all the chickpea flours. On the contrary, the nutritional composition of the four different chickpea flours (conventional, fine, coarse, precooked) was similar except for the dietary fiber content, which was relatively higher in the fine flour (Table 1). Previous study reported that the reduction of flour particle size can contribute to modify the total dietary fiber content in a broad range of ingredients, including cereals, legumes, nuts, vegetables, and fruits (Yao, Flanagan, Williams, Mikkelsen, & Gidley, 2023). The particle size distribution was similar in corn, rice, conventional, and precooked chickpea flours, with about 80% of the flour in the 125–425 μm size range and about 20% smaller than 124 μm. Chickpea fine flour was predominantly (87%) composed of particles <124 μm, while 99% of coarse chickpea flour's particles were larger than 124 μm (36% larger than 426 μm). In general, flour fractions <124 μm are expected to contain a prevalence of fractured cells with an abundance of free starch granules (Englyst, Kingman, & Cummings, 1992), while larger particle sizes may contain larger fractions of intact cells, whose structural integrity might favor starch containment and inhibit access to digestive enzymes (Capuano & Pellegrini, 2019; Dhital et al., 2016; Korompokis et al., 2019; Pellegrini et al., 2020; Rovalino-Córdova et al., 2018; Rovalino-Córdova et al., 2021).

Flours pasting curves are presented in Fig. 2, while pasting parameters of single flours are summarized in Table 1. The visco-amilograph profile of precooked corn flour indicated that corn flour starch gelatinization initiated at lower temperatures than in precooked rice and conventional chickpea flours (i.e., 70.6 ± 0.4 °C versus 78.1 ± 0.2 and 84.0 ± 0.7 °C, respectively; Fig. 2A and Table 1), and was more extensive, leading to the formation of a more viscous gel, as shown by the higher peak and final viscosities (Fig. 2A and Table 1). Precooked rice and conventional chickpea flours had a similar gelatinization pattern, but conventional chickpea flour gelatinization onset at higher temperature (i.e., 84.0 ± 0.7 vs 78.1 ± 0.2 °C) and led to a less viscous gel upon cooling (i.e., 113.3 ± 6.0 vs 232.0 ± 8.5 BU). The higher setback of precooked corn and rice flours demonstrated a higher pasting retrogradation than all the types of chickpea flours. The overall low breakdown of all flours indicated a good ability to withstand breakdown while heating and shearing (Adebowale, Sanni, & Oladapo, 2009). It is noteworthy that the viscoamylograph profile of the 50% corn: rice (3:2) and 50% conventional chickpea blend (Fig. 2A) very closely resembled that of rice flour, suggesting that the gelatinization and gelling behavior of the blend was dominated by rice flour contribution.

Plenty of studies have documented the effect of raw materials, flour particle size, and component interactions (such as starch-lipid and/or protein) on flour pasting properties (Ahmed, Taher, Mulla, Al-Hazza, & Luciano, 2016; Falade & Okafor, 2015; Hasjim, Li, & Dhital, 2013; Izydorczyk, MacGregor, & Billiaderis, 2001; Jekle, Mühlberger, & Becker, 2016; Mohammed, Ahmed, & Senge, 2014; Naguleswaran, Vasanthan, Hoover, & Bressler, 2013). In addition, differences in pasting properties were recorded among chickpea flours with different FP. Precooked and fine chickpea flours had gelatinization onset temperatures (i.e., 77.8 ± 0.4 and 78.4 ± 0.4 °C, respectively) lower than that of conventional (84.0 ± 0.7 °C) and, even more, of the coarse flour (89.0 ± 0.8 °C), thus supporting the evidence that preservation of intact cell structures delayed starch gelatinization possibly by hindering/retarding water diffusion in the food matrix. Starch granule extraction from chickpea cells (fine flour) favored the occurrence of a more extensive gelatinization (higher peak viscosity, Fig. 2B and Table 1), suggesting higher interactions with water leading to a more viscous gel (higher final viscosity, Fig. 2B and Table 1). On the contrary, encapsulation of starch in intact cell structures (coarse flour) resulted in less viscous gels both during heating (peak viscosity) and in the cooled gel (final viscosity, Fig. 2B and Table 1). Viscosity patterns of gelatinizing conventional and precooked chickpea flours were similar (Fig. 2B) but precooking favored the formation of a more viscous gel (Fig. 2B and Table 1). The higher setback of coarse and precooked flours displayed a higher paste retrogradation ability during cooling than that of conventional and fine flours (Table 1).

3.2. Pasta: cooking and physical characterization

Pasta with the same formulation and extruded in different shapes (i.e. fusilli, fusilli piccolo, caserecce, gnocchi sardi, and rigatoni) is presented in Fig. 1A, while pasta produced using different chickpea flours (i.e., fine, coarse, precooked, and conventional; FP) as rigatoni-shape is shown in Fig. 1B. Pasta cooking and technological quality in terms of OCT, cooking loss, moisture content, dimensional changes, color, hardness, adhesiveness, and thermal properties are summarized in Table 2 and are presented considering the independent effect of PS and FP.

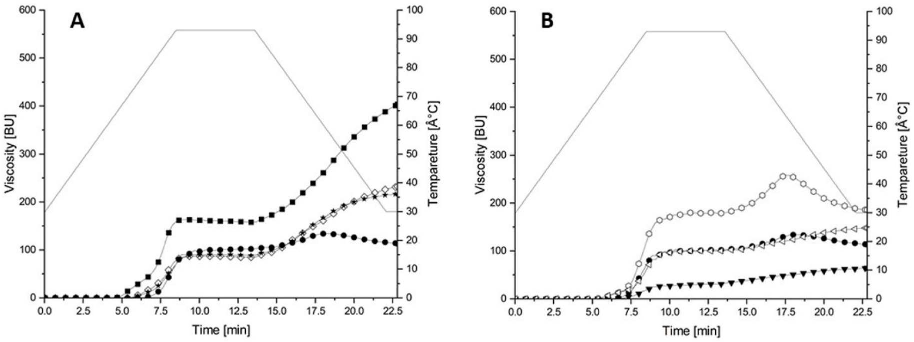

Fig. 2. Visco-amylograph profiles of different flours: —■— corn; —◇— rice; —★— corn-rice-conventional chickpea flour blend (50% w/w corn: rice [3:2] and 50% w/w chickpea flour); —●— conventional chickpea flour; —○— fine chickpea flour; —▼— coarse chickpea flour; —◁— precooked chickpea flour.

Table 2
Thermal properties, cooking quality and physic-chemical properties of cooked pastas: A) “*PS*” - pasta with different shapes (fusilli, fusilli piccoli, caserecce, gnocchi sardi, rigatoni) made with the same formulation and conventional chickpea flour; B) “*FP*” - rigatoni shaped pasta made using different chickpea flours (fine, coarse, precooked, and conventional).

Sample name	Cooking quality					Thermal properties of pastas				Physical property of cooked pasta				
	OCT (min)	Cooking loss (%)	Moisture content (%)	Length gain (%)	Thickness gain (%)	Onset T (°C)	Peak T (°C)	Offset T (°C)	Enthalpy (J/g dry starch)	L	a	b	Hardness (N/mm^2)	Adhesiveness ($J \times 10^{-3}$)
A - *PS*														
Fusilli	6.0	5.6 ± 0.0d	42.4 ± 1.0b	17.2 ± 1.1b	65.2 ± 2.5b	59.8 ± 0.5BCE	71.0 ± 0.6a	78.8 ± 0.6 ab	3.27 ± 0b	71.1 ± 2.5b	1.2 ± 0.5c	28.1 ± 2.1b	0.19 ± 0.04c	1.8 ± 0.4b
Fusilli piccoli	4.0	6.2 ± 0.1BCE	39.8 ± 0.3c	21.0 ± 2.3 ab	80.0 ± 5.2a	60.3 ± 0.5BCE	70.5 ± 0.6 ab	78.4 ± 0.6 ab	3.02 ± 0d	73.7 ± 1.4a	1.4 ± 0.5c	30.3 ± 1.2a	0.18 ± 0.03c	2.5 ± 0.7a
Caserecce	5.0	6.5 ± 0.3a	38.6 ± 0.2d	20.1 ± 4.8 ab	39.3 ± 2.1d	60.9 ± 0.5 ab	71.4 ± 0.6a	80.1 ± 0.6a	3.15 ± 0c	73.9 ± 1.5a	0.8 ± 0.7d	28.8 ± 2.7b	0.16 ± 0.03d	1.7 ± 0.6b
Gnocchi sardi	7.5	6.4 ± 0.1 ab	40.6 ± 0.2c	25.0 ± 0.4a	58.6 ± 1.5c	59.1 ± 0.5c	69.2 ± 0.6b	79.3 ± 0.6 ab	3.25 ± 0b	70.4 ± 1.7b	2.0 ± 0.8b	28.4 ± 2.7b	0.24 ± 0.03b	1.2 ± 0.4c
Rigatoni[§]	8.0	6.1 ± 0.1c	44.2 ± 1.1a	16.1 ± 3.5b	54.9 ± 2.5c	61.8 ± 0.5a	70.5 ± 0.6 ab	77.8 ± 0.6b	3.53 ± 0a	67.8 ± 1.0c	3.8 ± 0.4a	29.0 ± 1.6b	0.68 ± 0.05a	0.6 ± 0.3d
B – *FP*													Hardness (N)	
Fine	8.5	6.2 ± 0.1B	45.4 ± 0.3C	13.4 ± 0.4AB	56.2 ± 0.4B	59.1 ± 0.5B	72.0 ± 0.6A	79.2 ± 0.6A	3.1 ± 0B	67.5 ± 1.2A	2.6 ± 0.3D	26.9 ± 1.6B	7.8 ± 0.4C	0.4 ± 0.2C
Coarse	7.5	5.5 ± 0.1C	46.9 ± 0.6B	16.4 ± 0.6A	68.6 ± 0.6A	61.1 ± 0.5A	71.4 ± 0.6A	78.7 ± 0.6A	3.0 ± 0B	64.7 ± 1.1B	5.9 ± 0.4A	25.6 ± 0.9C	8.6 ± 1.2B	0.5 ± 0.2AB
Precooked	9.0	7.0 ± 0.0A	48.8 ± 0.1A	12.4 ± 1.8B	54.6 ± 1.6B	59.6 ± 0.5B	69.3 ± 0.6B	79.3 ± 0.6A	2.9 ± 0C	67.0 ± 0.5A	4.4 ± 0.3B	26.8 ± 1.1B	9.4 ± 1.1A	0.5 ± 0.2AB
Conventional[§]	8.0	6.1 ± 0.1B	44.2 ± 1.1D	16.1 ± 3.5AB	54.9 ± 2.5B	61.8 ± 0.5A	70.5 ± 0.6AB	77.8 ± 0.6A	3.5 ± 0A	67.8 ± 1.0A	3.8 ± 0.4C	29.0 ± 1.6A	8.8 ± 0.8B	0.6 ± 0.3A

OCT: Optimal cooking time.
Data are means of the triplicates ± standard deviation.
L: lightness; a: (+) redness, (−) greenness; b: (+) yellowness, (−) blueness.
Means followed by different letters in each table section and column (lowercase for A-PS, capital letters for B-FP) are significantly different at $p < 0.05$.
[§] The same sample.

3.2.1. *Effect of pasta shape*

No marked differences were found in the overall appearance of pasta with different PS. On the contrary, pasta OCT was affected by the PS (Table 2), in line with previous findings (Shreenithee & Prabhasankar, 2013; Suo et al., 2021). The OCT ranged from 4 to 8 min, where rigatoni had the longest OCT most likely due to a longer time needed for water to diffuse and penetrate pasta matrix because of its large piece size. Because of their small size, fusilli piccoli required a shorter cooking time (i.e., 4 min). Cooking losses into water were different ($p < 0.05$) among pasta shapes (Table 2), but, being in the range of 5.6–6.5 %, all GF products can be considered of good quality (Boukid et al., 2019). Interestingly, cooking loss was not proportional to the cooking time:

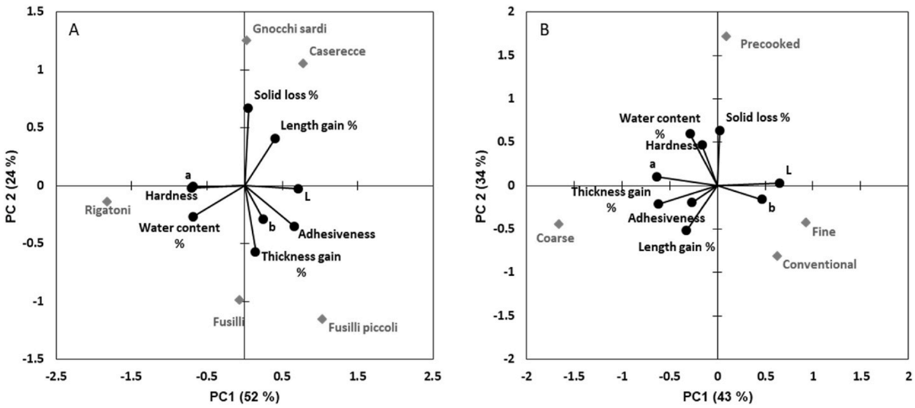

Fig. 3. PCA biplot based on cooking and technological quality of pasta: A) “*PS*” - pasta with different shapes (fusilli, fusilli piccoli, caserecce, gnocchi sardi, rigatoni) made with the same formulation and conventional chickpea flour; B) “*FP*” - rigatoni shaped pasta made using different chickpea flours (fine, coarse, precooked, and conventional).

caserecce, for instance, although had a relatively short OCT (5 min) and low water uptake (38.6 ± 0.2% moisture content), displayed the highest cooking loss among all GF pastas, while rigatoni, that required 8 min to cook and absorbed the most water (44.2 ± 1.1 % moisture content), had a 6.1 ± 0.1 % cooking loss (Table 2). This can be better explained by the PS effect, as shown in the PCA figure (Fig. 3A). Cooking loss was positively correlated with caserecce and gnocchi sardi shaped pasta but negatively with rigatoni and fusilli shaped pasta. Moisture content of cooked pastas (Table 2) was significantly affected by the PS and cooking time: a shorter OCT (e.g., fusilli piccolo and caserecce) resulted in lower water absorption as compared to longer cooked pasta (e.g., fusilli and rigatoni). The PCA results further interpreted the shape effect with a positive correlation between moisture content and rigatoni and fusilli. These results suggested that pasta shape has an important impact on pasta cooking quality likely induced by different microstructural arrangements (affecting especially starch granules and proteins) occurring in the shaping phase of extrusion, in line with previous indications (Shreenithee & Prabhasankar, 2013).

Dimensional changes of pasta pieces upon cooking were also shape-dependent (Table 2). Rigatoni and fusilli expanded less in length ($p < 0.05$) than the other 3 pastas, while gnocchi sardi had the greatest length gain (i.e., 25.0 %; $p < 0.05$), which correspond, respectively, to their negative and positive correlation in the PCA biplot (Fig. 3A). Thickness gain (%) is known to be predominant over length expansion in GF pasta (Morreale et al., 2019; Suo et al., 2021), and it was the least in caserecce (about 39%) and the greatest in fusillo piccolo (80%). A negative and positive correlation with thickness gain was observed for caserecce and fusillo piccolo, respectively (Fig. 3A). As expected, pasta color (L, a, b) was not markedly affected by the different PS, although statistically different in value. This was also reflected in a relatively weak correlation in PCA biplot (Fig. 3A) and in the visual appearance of samples as presented in Fig. 1A.

Thermal properties are presented in Table 2. All samples exhibited, upon heating, an endothermic peak in the 60–80 °C range. (Bresciani, Giuberti, Cervini, & Marti, 2021) reported that 100% legume-based GF pasta exhibited a gelatinization peak in the range of 63–80 °C, in line with present findings. In addition, melting enthalpies in the range of 3.02–3.53 J/g dry starch were reported, which can be associated with the melting of the non-gelatinized starch fraction after cooking. These differences in the melting enthalpy among the different pasta samples indicated a slight effect of the PS, thus allowing to conclude that all pasta samples were characterized by the presence of a comparable degree of crystalline starch upon cooking to OCT, irrespective of the different PS.

Considering textural attributes, cooked pasta hardness and adhesiveness were impacted by PS ($p < 0.05$). Rigatoni was the hardest (0.68 ± 0.05 N/mm^2) while caserecce the softest (0.16 ± 0.03 N/mm^2) samples as compared to the comparable fusilli and fusilli piccolo (0.19 ± 0.04 and 0.18 ± 0.03 N/mm^2), and slightly harder gnocchetti (0.24 ± 0.03 N/mm^2). Moreover, a strong correlation between hardness and rigatoni was observed by PCA analysis (Fig. 3A). The rigatoni hollow shape and the consequent cutting of a double pasta layer in the experimental protocol might explain the harder texture of rigatoni. Adhesiveness of pasta was significantly different among the different pasta samples with the least adhesive product being rigatoni, whereas the stickiest was fusilli piccolo, as reflected in their correlation in PCA result. The longer cooking time of rigatoni might have favored a more important removal of leached starch from the pasta surface, resulting in a less sticky surface.

3.2.2. *Effect of chickpea flour particles*

Using chickpea flours with different FP together with corn:rice flour mixtures (50% w/w chickpea flour and 50% w/w corn: rice [3:2]) to produce pastas with the same shape (rigatoni) had a slight effect on raw pasta appearance (Fig. 1B). The use of coarse chickpea flour resulted in a more heterogeneous appearance, while fine and precooked chickpea flour in a more homogeneous surface. Chickpea flour FP slightly affected the pasta OCT that ranged from 7.5 to 9.0 min for pasta containing coarse and precooked chickpea flours (Table 2). It is worth pointing out that the OCT increased with decreasing flour particle size and it was the longest in the case of the precooked flour, possibly because of the more compact microstructure, which might have hindered water diffusion resulting in a longer OCT, in line with previous findings (Bresciani et al., 2021). Different FP of chickpea flour slightly altered pasta cooking behavior compared to conventional flour, probably because of slightly different functional properties (e.g., water absoption and rate of absorption; (Jalgaonkar & Jha, 2016). Similar (about 6.1 %) cooking losses were observed in fine and conventional GF pasta samples, whereas they were lower in coarse flour-containing pasta (i.e., 5.5 %; $p < 0.05$) and greater in precooked flour-containing pasta (i.e., 7.0 %; $p < 0.05$), in line with previous studies (Jalgaonkar & Jha, 2016). Present findings reflected the length of cooking and supported the hypothesis of lower cooking losses when cell structural integrity (and starch containment within) is preserved. PCA results further revealed a FP effect with a stronger positive correlation between cooking loss and pasta containing precooked chickpea flour and a negative correlation with pasta containing coarse chickpea flour (Fig. 3B). Precooked chickpea flour in GF pasta caused the greater cooking loss, probably because of the more accessible gelatinized starch matrix that was more likely to be washed out and released in the boiling water, compared to the other types of flour. Using the other chickpea flours (conventional, fine, coarse) implied that starch gelatinization occurred while cooking, making the gelatinized starch matrix accessible for water wash-out for a shorter time. The higher confinement of starch granules in intact cell structures and the shortest cooking time are likely responsible for the lower cooking loss reported in coarse pasta. In addition, cooking losses in the 5.5–7.0 % for all pastas make them considered as good quality products according to previous report (Boukid et al., 2019).

Compared to pasta with conventional chickpea flour, the slightly higher water absorption of fine chickpea flour containing pasta was probably linked to the longer OCT (Table 2) and easier water penetration in the pasta matrix. The opposite position of water content from fine and conventional flour incorporated pasta in PCA biplot figure (Fig. 3B) proved the weakening effect of those two flours on water absorbability of products as compared to the other two flours. The higher water uptake found in the pasta containing precooked chickpea flour was expected because of the higher affinity for water on pregelatinized amorphous starch as well as of its longer cooking time. Coarse and conventional flour containing rigatoni extended, upon cooking, more in length than that of the other two samples (i.e., fine and precooked counterparts), while a comparable thickness extension was observed in fine, precooked and control samples whereas coarse pasta displayed a more important thickening (Table 2). Considering pasta color, lightness (L), redness (a) and yellowness (b) ranged from 64.7 to 67.8, 2.6 to 5.9 and 25.6 to 29.0, respectively, in which the variance is small even though statistically different. It might be concluded that FP only marginally altered pasta color as confirmed by PCA result (Fig. 3B) where four pastas were slightly correlated with color coordinates.

Thermal properties of rigatoni made with the different flour types were very similar among samples, in line with the results outlined in the PS section (Table 2). Using conventional chickpea flour resulted in a slightly higher melting enthalpy than fine, precooked and coarse flours in rigatoni-shaped pasta. It can be concluded that all pasta samples were characterized by the presence of a comparable degree of crystalline starch after cooking to optimal cooking time, irrespective of the FP used in the formulation.

Textural attributes of the four GF pasta samples formulated with the four different flour types were in the range of 7.8–9.4 N for hardness and in the range of 0.4–0.6 J × 10^{-3} for adhesiveness. Precooked chickpea flour containing pasta was the hardest (9.4 N/mm^2; $p < 0.05$) among samples, while fine chickpea flour containing pasta was the softest (7.8 N/mm^2; $p < 0.05$) with the least adhesive (0.4 J × 10^{-3}; $p < 0.05$) compared to conventional pasta which is likely because of its higher fiber content (Ciccoritti, Nocente, Sgrulletta, & Gazza, 2019). As compared to other characteristics, a relatively lower correlation was observed from PCA biplot between texture and pasta containing four flours (Fig. 3B), which might demonstrate a relatively lower effect of FP on texture properties of cooked pasta.

3.3. *In vitro starch and protein digestibility of cooked pasta*

Total starch and protein contents of all pasta considered in this study were, respectively, in the range of 50–53 g/100 g dry matter (DM) and 13–15 g/100 g DM (Table 3), with little variations that, although significant, can be ascribable to the variability associated to the slightly different nutrients content of the different chickpea flour types (Table 1). The IVSD and IVPD results are shown in Table 3.

3.3.1. *Effect of pasta shape*

The starch digestion parameters related to the cooked pasta samples (on a dry matter basis) are reported in Table 3 as RDS, SDS, RS, AS together with the percentage of SDS/AS and RS/TS. The different PS markedly affected the starch fraction content (*A-PS*, Table 3). In particular, fusilli piccoli were characterized by the greatest RDS (i.e., 21.5 g/100g DM; $p < 05$) and the lowest RS contents (i.e., 0.6 g/100g DM; $p < 0.05$) with respect to all the other samples. The influence of the PS on the starch digestibility and the subsequent glycemic response modulation has been already described in literature (Dodi et al., 2023; Vanhatalo et al., 2022). Consequently, compared to the other four pasta, fusilli piccoli can likely result in a higher blood sugar levels upon ingestion due to its higher RDS and therefore the related rapidly available glucose content. Noteworthy, to meet the health claim of “reduction of postprandial glycemic responses” declared by the European Food Safety Authority (EFSA) in 2011 for high carbohydrate cereal-based foods, at least 14 % (of total starch) should be in the form of RS, while the health claim related to “slowly digestible starch in starch-containing foods” and “reduction of postprandial glycemic responses” is defined for products with at least 40% of AS as SDS being helpful to induce a lower postprandial glycemic response.

The RS content closer to 14% on TS found in rigatoni shaped pasta, can contribute to meet the health claim “reduction of postprandial glycemic responses” declared by EFSA. Modifying the pasta shape could strongly affect the internal pasta structure due to mechanical and thermal forces involved during the extrusion, which can contribute to potentially altering the digestibility of starch (Petitot, Abecassis, & Micard, 2009). Similarly, pasta shape has already been reported to influence the enzyme susceptibility of starch in the gluten-containing pasta (Petitot et al., 2009). In addition, the SDS/AS in all samples with different PS exceeded the percentage of 55%, supporting the health claim related to “reduction of postprandial glycemic responses” mentioned above. A different *in vitro* starch digestibility has been previously reported between spaghetti and lasagne, with lasagne being hydrolyzed slightly more than spaghetti in the first 180 min of enzyme incubation (Fardet et al., 1998). Not only pasta shape, but pasta size has also been reported to influence susceptibility of starch to α-amylase where small pasta size led to higher enzyme susceptibility (Colonna et al., 1990). Moreover, it is important to highlight that different pasta shape can mediate *in vivo* a different structural breakdown during mastication thus leading to the production of different particle size of pasta in the bolus, which results in a significantly different starch digestion and glycemic response (Suo et al., 2021; Vanhatalo et al., 2022). In addition, the cooking process can result in a different reorganization of starch structure because of starch gelatinization and starch polymers rearrangement on cooling (Marti et al., 2011), and to possible changes within the protein-starch network in pasta (Fardet et al., 1998), thus leading to a different *in vitro* starch digestion.

Significant differences in IVPD were observed among GF pasta with different PS, (Table 3). Fusilli piccoli had the highest IVPD (i.e., 95.7 %; $p < 0.05$), whereas rigatoni and gnocchi sardi had the lowest IVPD (i.e., on average 88.5 %). The differences in the IVPD among samples with different PS could be related to possible changes occurring in the protein network reticulation during the extrusion process. In particular, the extrusion pressure and shearing stress during pasta extrusion can be different when different shaping dies for pasta production are applied, which can result in different elongational stress, and consequently leading to a different pasta structure and protein solubility (Petitot et al., 2009). Different extrusion conditions have been reported to affect protein solubility identified by a loss of solubility of globulins (Dexter & Matsuo, 1977). Accordingly, lasagne had slightly higher protein

Table 3

In vitro starch and protein digestibility of cooked pasta samples: A) “*PS*” - pasta with different shapes (fusilli, fusilli piccoli, caserecce, gnocchi sardi, rigatoni) made with the same formulation (i.e., conventional chickpea flour); B) “*FP*” - rigatoni shaped pasta made using different chickpea flours (fine, coarse, precooked, and conventional).

Sample name	*In vitro* starch digestion							*In vitro* protein digestion	
	Total starch	RDS	SDS	RS	AS	RS/TS	SDS/AS	Total protein	IVPD
	(g/100g DM)	(g/100g DM)	(g/100g DM)	(g/100g DM)	(g/100g DM)	(%)	(%)	(g/100g DM)	(%)
A - PS									
Fusilli	52.6 ± 0.6a	18.9 ± 0.3b	32.7 ± 0.4a	1.1 ± 0.4b	51.6 ± 0.7a	2.0 ± 0.8cd	63.4 ± 0.3b	14.6 ± 0.2BCE	93.1 ± 0.3b
Fusilli piccoli	53.3 ± 0.4a	21.5 ± 0.5a	31.3 ± 1.0a	0.6 ± 0.4c	52.8 ± 0.6a	1.1 ± 0.7d	59.3 ± 1.4c	15.5 ± 0.5a	95.7 ± 0.6a
Caserecce	52.6 ± 0.5a	16.5 ± 1.3c	32.6 ± 1.6a	1.4 ± 0.3 ab	49.2 ± 1.5b	2.8 ± 0.7c	66.4 ± 2.6a	14.9 ± 0.1 ab	93.0 ± 0.5b
Gnocchi sardi[§]	52.8 ± 0.2a	18.4 ± 0.7b	28.5 ± 0.3b	3.4 ± 0.5a	46.9 ± 0.5c	6.7 ± 1.1b	60.8 ± 1.0c	14.3 ± 0.2c	89.1 ± 0.5c
Rigatoni	51.4 ± 0.5b	17.1 ± 0.9c	27.2 ± 0.7b	7.1 ± 0.6d	44.3 ± 0.6d	13.9 ± 1.2a	61.5 ± 1.7BCE	15.3 ± 0.1a	88.1 ± 0.3c
B - FP									
Fine	52.8 ± 0.8A	16.6 ± 0.3A	32.9 ± 1.0A	7.5 ± 0.2AB	49.5 ± 0.7A	13.2 ± 0.3C	66.4 ± 1.0A	12.6 ± 0.1C	87.6 ± 0.0A
Coarse	51.9 ± 0.3AB	14.8 ± 0.5B	28.5 ± 0.6C	8.0 ± 0.8AB	43.3 ± 1.0C	15.5 ± 1.5AB	65.8 ± 0.5A	13.4 ± 0.5B	88.5 ± 0.6A
Precooked	52.7 ± 0.2A	14.5 ± 0.7B	30.4 ± 0.9B	8.5 ± 0.8A	44.9 ± 0.7B	15.9 ± 1.4A	67.8 ± 1.6A	13.6 ± 0.1B	87.5 ± 0.5A
Conventional[§]	51.4 ± 0.5B	17.1 ± 0.9A	27.2 ± 0.7D	7.1 ± 0.6B	44.3 ± 0.6BCE	13.9 ± 1.2BCE	61.5 ± 1.7B	15.3 ± 0.1A	88.1 ± 0.3A

Data are means of the triplicates ± standard deviation.

Means followed by different letters in each table section and column (lowercase for A-PS, capital letters for B-FP) are significantly different at $p < 0.05$.

RDS: rapidly digestible starch.

SDS: slowly digestible starch.

RS: resistant starch.

AS: available starch.

RS/TS: resistant starch/total starch.

SDS/AS: slowly digestible starch/available starch.

DM: dry matter.

[§] The same sample.

hydrolysis than spaghetti (Fardet et al., 1998). Authors explained these discrepancies arguing that proteins could bind to the insoluble components of products leading to a different *in vitro* digestibility.

3.3.2. Effect of chickpea flour particles

Considering the effect of chickpea flour particles (*B-FP*, Table 3), the highest SDS and AS contents ($p < 0.05$) were obtained in rigatoni pasta formulated with fine FP chickpea flour. Rigatoni obtained with conventional chickpea flour resulted in a lower SDS/AS (i.e., 61.5; $p < 0.05$). In addition, both rigatoni formulated with coarse and precooked chickpea flours exhibited a RS content higher than the threshold of 14% on a total starch basis, thus supporting the related health claim as mentioned above. In general, the particle size can affect the *in vitro* starch hydrolysis, being typically related to the available surface area for enzymatic action, with fine particles, having more surface area compared with medium and coarse particles, leading to greater extent of enzyme susceptibility (Al-Rabadi, Gilbert, & Gidley, 2009). However, within a complex food system, other factors can mutually play a role in influencing the degree of enzymatic starch access, including, but not limited to, the type of starch, the cooking process, the level of starch gelatinization, and the presence of non-starch-components (mainly protein and dietary fiber; Aguilera, 2019; Rainero et al., 2022), thus hiding, or at least reducing, the solely effect of FP. In addition, the limited effect of FP can be also related to the fact that the 50% of blends, in formulations, were precooked corn and precooked rice flours which might contribute to alleviate or cover up the FP effect.

Concerning the effect of FP on IVPD, no differences were recorded among samples (Table 3), being on average of 88.0 %. Even if it has been reported that the kinetics of *in vitro* protein digestion can be modify as a function of the particle size in raw ingredients (Tinus, Damour, van Riel, & Sopade, 2012), different authors indicated that similar extrusion and cooking conditions can lead to a comparable *in vitro* protein digestibility in food systems characterized by different particle size (Byars, Singh, Kenar, Felker, & Winkler-Moser, 2021).

This work displayed the operability of modifying pasta technological and nutritional property by means of structuring PS or FP. However, some limitations of the work are worth highlighting. Firstly, a deep investigation of different PS (including also long pasta) should be considered in order to have a complete picture of the effect of PS and FP on the technological parameters and nutritional characteristics. Further studies are also needed to better explore the effect of chickpea inclusion at higher level in GF pasta formulation and to explore possible differences not only concerning technological aspects, but also nutritional implications related to macroscopic (PS) and microscopic (FP) differences at greater chickpea inclusion levels. Finally, for the identification of the different starch fractions, the method proposed by Englyst et al. (1999) and mentioned in the EFSA opinion was used, however a slightly revised method has been recently published (Englyst et al., 2018) that could be also considered for future studies.

4. Conclusion

In this work, five short pasta (rigatoni, fusilli, fusilli piccolo, caserecce, gnocchetti sardi) and four chickpea flours were taken as subjects to investigate shape and flour particle effect, respectively, to product's quality and *in vitro* starch and protein digestibility in chickpea-corn-rice GF products. Pasta shape was found to strongly impact pasta technological quality as well as *in vitro* starch and protein digestibility, whereas chickpea flour particles slightly affected these attributes. The inclusion of different chickpea flours at a level of 50% into GF pasta was successful and all products were identified with good cooking quality. Considering the different characteristics among samples, pasta shape should be taken into consideration by food industry to design food products as a mean to modify physic-chemical and nutritional attributes. However, it is suggested to carry out more research activities considering other pasta shapes including both short and long pasta products to further support these outcomes.

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CRediT authorship contribution statement

Xinying Suo: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Margherita Dall'Asta:** Data curation, Investigation, Methodology, Writing – review & editing. **Gianluca Giuberti:** Data curation, Formal analysis, Methodology, Writing – review & editing. **Michele Minucciani:** Conceptualization, Funding acquisition, Resources, Writing – review & editing. **Zhangcun Wang:** Supervision. **Elena Vittadini:** Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Supervision.

Declaration of competing interest

We are reporting that author Michele Minucciani works in the Massimo Zero srl, a gluten free pasta manufacturer, a company that may be affected by the research reported in the enclosed paper. Other authors do not have conflict of interests to report.

Data availability

Data will be made available on request.

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